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Nitrogen Fertilization Studies in Dryland Winter Wheat and Potential Nitrogen Losses from the Soil at the Blue Creek Experimental State in Northern Utah

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NITROGEN FERTILIZATION STUDIES IN DRYLAND WINTER WHEAT AND POTENTIAL NITROGEN LOSSES FROM THE SOIL AT THE BLUE CREEK EXPERIMENTAL STATION IN NORTHERN UTAH

by

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Subhawat Intalap

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ABSTRACT

Nitrogen Fertilization Studies in Dryland Winter Wheat and Potential Nitrogen Losses from the Soil at the Blue Creek Experimental Station in Northern Utah

by

Subhawat Intalap, Doctor of Philosophy

Utah State University, 1976

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This study compared the effects of nitrogen sources on the available inorganic soil nitrogen, nitrogen movement, nitrogen losses, and wheat yields when nitrogen fertilizers were applied to soil planted to dryland winter wheat at the Blue Creek Experimental Station in northern Utah.

In the fall 1973 soil samplings, the fertilizers producing the largest mineral nitrogen contents in the 0-30 cm soil depths were ammonium nitrate > ammonium sulfate > S-coated urea, when they were broadcast at the practical rate of 56 kg N/ha. There was no increase in the mineral nitrogen at the deeper depths in the fall or at any depth in the following spring. Statistically, the three nitrogen sources did not increase grain yield significantly but did increase grain protein content and nitrogen content in grain.

Ammonium nitrate and potassium bromide at the rates of 400 kg N and 200 kg Br/ha were broadcast to soil planted to winter wheat in October 1974.

Nitrate-nitrogen and bromide distribution patterns in the soil profile looked alike in May 1975. These showed that their movements were similar. Considerable nitrate-nitrogen (35 percent of the added nitrogen) had moved down below the 120 cm depth. The highest nitrate-nitrogen concentrations were found at the 45 to 90 cm depth. There seems to be evidence that nitrate-nitrogen and bromide had moved deeper than the 150 cm depth.

Ammonia-nitrogen losses from nitrogen fertilized soils were conducted in the laboratory. Ammonium sulfate, ammonium nitrate, or urea applied to the soil surface lost ammonia-nitrogen differently. From noncalcareous soil, the ammonia-nitrogen loss was greatest from urea. From calcareous soil or soils receiving carbonates or high soil pH by the addition of sodium hydroxide solution, the greatest losses were from ammonium sulfate. High losses were favored by high temperatures and longer periods of moist soil. The total amounts of water lost from the soil was not closely related to the total ammonia-nitrogen loss during two weeks. No loss of ammonia-nitrogen occurred when nitrogen fertilizers were applied at a 2.5 cm depth or deeper. The ammonia-nitrogen losses were also greatly reduced when nitrogen fertilizers applied to the soil surface was followed by irrigation or heavy rainfall.

In the field, the higher temperatures increased the ammonia-nitrogen losses from ammonium sulfate, ammonium nitrate, and urea when applied to both a noncalcareous and a calcareous soil. However, the loss from calcareous soil was reduced by irrigation following fertilizer application. No ammonia-nitrogen

was observed when ammonium sulfate was applied at a 2.5 cm soil depth, despite of the high soil temperature during the day time in moist soil. Rapid drying of the moist soil surface quickly reduced the losses per day.

(192 pages)

INTRODUCTION

Nitrogen (N) is commonly the most important fertilizer element applied to soil, its effects being manifested quickly in plant growth or appearance and ultimately on crop yields. At the present time the marked increases in crop yields per unit area may be attributed in large part to the steadily increasing rates of addition of nitrogen in commercial forms. Phosphorus, potassium, and the other essential plant nutrients are also necessary, of course, and essential for maximum efficiency in the use of nitrogen.

The nitrogen cycle in soil is an integral part of the overall cycle of nitrogen in nature. The primary source of soil nitrogen is the atmosphere, which contains about 80 percent by volume of molecular N. Under natural conditions, gains in soil nitrogen occur mainly through the fixation of elemental nitrogen by microorganisms and from the ammonia (NH_3) and nitrate nitrogen (NO_3-N) dissolved in the precipitation.

The nitrogen in soil is largely bound in organic matter. In general, only a small amount will exist in available forms at any one time. In some soils, such as some Mollisols, larger quantities of nitrogen are present than in other soils, such as Spodosols. Usually, when naturally fertile land is cultivated, the nitrogen content of the soil as well as crop yields decline rapidly. The extent of nitrogen decrease (decrease in organic matter) depends on climatic conditions, cultural practices and soil types.

A practice which relies only on soil nitrogen reserves to meet the nitrogen requirements of crops cannot be effective very long in producing high yields of crops. Before the middle of this century, biological nitrogen fixation and animal manures were the chief means of supplying nitrogen for cultivated crops. In recent years, nitrogen fertilizers have become available, which, when used to augment the nitrogen supplied by natural processes, can increase yields and improve the quality of crops. A major concern of present-day farmers is the effective use of nitrogen fertilizers.

Usually various forms of commercial nitrogen fertilizers are used. As one of the important expenditures in crop production, the efficiency with which nitrogen is utilized in crop production is a subject that has been of intense interest to agronomists for many years. Nitrogen loss from nitrogen fertilizers applied to soils is an important factor of nitrogen fertilizer efficiency.

Low recovery in crops of the added N is believed to be attributed in considerable part to gaseous losses, one of which is in the form of ammonia from calcareous or sodic soils following application on the surface or at shallow depths. The quantities lost depend on variations in environmental conditions; consequently environmental conditions partially regulate the efficiency of N utilized by crops.

In warm semi-arid regions a considerable amount of NH_3 loss may occur because of the alkaline soil reaction (pH), rapid soil moisture loss (drying), and the high temperature during the growing season. Lower yields of winter wheat from fall application of N fertilizer compared to spring application of fertilizer may be partly due to NH_3 loss prior to the active N absorption by wheat which occurs

in late spring. The soils with carbonates seem to be particularly subject to NH_3 losses. Nitrate nitrogen leaching loss can also occur during the period of frequent intensive rainfall and period of rapid snow melting in early spring.

Winter wheat is one of the major crops of Utah. For more than 70 years winter wheat has been grown on the dry lands of the state. It is about the only crop grown on these lands, usually under an alternate cropping-fallow system. With a continual nitrogen depletion from the soil, without fertilization there will be smaller yields and grain of inferior quality. Hence, nitrogen may be one of the limiting factors in wheat production in Utah. Yet, the relationship of available water and response to added fertilizers is also a regulating factor in fertilization. This study compares the effects of nitrogen sources on the available inorganic soil N, N movement, N losses, and wheat yields when fertilizers are applied to soils planted to dryland winter wheat at the Blue Creek Experiment Station.

REVIEW OF LITERATURE

One of the early "nitrogen balance sheets" for the harvested crop areas of the United States published by Lipman and Conybeare in 1936 was summarized by Allison (1955). It emphasized that in many cases quantitative information was inadequate for arriving at accurate values for the quantities of N gained and lost through the various transformations. The net annual loss in their N balance sheet for cropped soils was 50 Kg N/ha per year. Allison (1966) also reviewed the N balance data from long term lysimeter experiments which pointed out that considerable amounts of N losses from normal, well-aerated soils may be due to volatilization. The unaccounted-for N, aside from that lost by leaching, was shown to escape in several forms: as ammonia, chiefly from alkaline soils; as N_2O and N_2 through denitrification; and, to a lesser extent, as NO formed by the chemical decomposition of nitrites. More recent studies have helped clarify these losses more specifically.

Recovery of N Applied to Soils

In general, it may be said that rather marked progress has been made both in obtaining more accurate N balance data and in determining the mechanisms by which N is lost. Much of this progress may be attributed to the rather general adoption of the techniques using labelled nitrogen, ^{15}N. This system of experimentation greatly increases the accuracy with which small amounts of fertilizer N or

other added N can be detected in the presence of much larger amounts of soil N. It also discriminates between man-added N and other N added as a result of nonsymbiotic N fixation, absorption of N gases from the air, or N dissolved in the rainfall. In addition, the tracer system permits both easy identification and quantitative determination of any N gases evolved from the fertilizer N, provided, of course, that they can be collected. Other instruments that have been used effectively in N studies include the infrared spectrometer and the gas chromatograph.

The recoveries of added fertilizer N in pot experiments using ^{15}N- labelled sources were reviewed by Allison (1966). He reported that the N recoveries, including that removed by the crop and that left in the soils after harvest, were in the range of 53 to 100 percent, but only rarely was all the added labelled N accounted for. In most studies where the investigators expressed an opinion, low recoveries were attributed to N losses by denitrification. Carter et al. (1962), studying the recovery of ^{15}N from soil under field conditions, found that the recoveries of ^{15}N added to the 32 plots ranged between 85.3 and 92.9 percent and averaged 89.5 percent. They believed that the unrecovered N was lost in gaseous forms and the deficit was not due to error in technique.

In spite of some high recovery percentages, it has been concluded that crops seldom recover more than half of the fertilizer N added to cultivated soils during the first year (Carter et al., 1963). The other half may be: (1) leached beyond the root zone; (2) tied up in soil organic matter; or (3) lost in gaseous forms.

Influence of soil texture

Nash and Johnson (1967) studied the influence of soil texture on the N recovered from fertilizer NH_4^+ or NO_3^- by several grass species grown on calcareous soils (pH 7.5) in the absence of nitrification. They concluded that soil texture had no influence on the added N recovered from nitrate nitrogen, but, when ammonium nitrogen (NH_4-N) was the fertilizer source, increased N amounts were recovered from the fine-textured soils. N recoveries from the nitrate and ammonium forms were 78 and 48 percent, respectively of the N applied. The lower N recovery from the ammonium form was attributed to NH_3 volatilization from coarse-textured calcareous soils. Very poor N recoveries (about 7 to 50 percent), due to N losses by denitrification following rain or irrigation in the field conditions, were obtained from fine-textured soils. In contrast, on a fine sandy loam the N recovery was about 80 percent (Viets, 1960).

Grable and Johson (1960) also concluded that the efficiency of recovery of applied NO_3-N was negatively correlated with clay percentage and specific surface area of the soils; the N losses included loss by denitirification. The average N efficiency measured as uptake by plants on 14 different soils in pot experiments was 77 percent. Better efficiencies were reported by Terman and Brown (1968) who had recoveries of fertilizer N of 90 percent from fine sandy loam and 85 percent from silty clay loam.

Influence of fertilizer sources

The fertilizer N source applied may influence N recovery in the soil-plant system. Carter et al. (1963), using tagged ammonium sulfate [$(NH_4)_2 SO_4$]and

sodium nitrate ($NaNO_3$), applied the fertilizers to soils cropped to sudan grass. Two months later from 85 to 92 percent of the fertilizer N was recovered. Losses were the same for both $(NH_4)_2SO_4$ and $NaNO_3$. Carter et al. (1967) studied the recovery of fertilizer ^{15}N under field conditions using sites enclosed by large steel cylinders. They found that recovery of the fertilizer N after 8 months ranged from 88 to 96 percent, but dropped as low as 77 percent after 10 months. Recovery of the fertilizer N was greater from ammonium sources than from nitrate sources.

N uptake by ryegrass from three tagged ammonium fertilizers was observed by Tyler and Broadbent (1958). The greatest yield of ryegrass and the highest recovery of N were obtained when $(NH_4)_2SO_4$ was applied. No real difference was observed in the percent recovery of N from ammonium hydroxide (NH_4OH) and ammonium nitrate (NH_4NO_3). The results of Lehr (1950), however, illustrated that the crop recovered much less N from ammonium materials than from nitrate fertilizers. Low recovery from ammonium materials was caused by NH_3 volatilization from lime soils.

Broadbent and Nakashima (1968) found that with surface application the uptake of fertilizer N in plant tops varied from 35 to 71 percent; nitrate sources supplied the greater percentages. Ammonium sources had losses when they were applied to the soil surface.

Westerman et al. (1971), comparing the efficiency of urea and oxamide in the field with sorghum as a test crop, found that 51 percent of the N added as urea was recovered in the crops and 28 percent remained in the soil. The

corresponding figures for oxamide were 52 and 41 percent. When NH_4NO_3 was the N source, the recoveries of fertilizer N on forage grass species were 48.5, 71.8, and 66.6 percent for timothy, bromegrass, and orchardgrass, respectively (George et al., 1973).

Influence of soil moisture

Thomas and Heilman (1967) reported that when low levels of N were present, a high soil moisture content reduced N absorption or N availability to sweet pepper. They suggested that the inhibiting effect of high soil moisture on N uptake was overcome by the application of high rates of N. Therefore, moisture and N application rates may affect the recovery of fertilizer N.

Srivastava and Singh (1971) found that N recoveries by sorghum and oats in the field were 38 and 43 percent, respectively. The low recoveries were due to leaching of the N which was applied at sowing.

Isotopic studies of the N balance in a cracking clay (clay 74 percent, pH 8.5, and moisture content at 56 percent) were carried out by Craswell and Martin (1975a, 1975b) as pot experiments in a glasshouse. Added NO_3-N and NH_4-N were almost completely recovered (about 97 to 99 percent) from the soil and wheat plant. Even at 63 percent moisture, which should favor denitrification, almost complete recovery of added ^{15}N was found. Using a lysimeter from which all gases were collected, less than 0.2 μgN/g soil was lost by denitrification, and only 0.16 percent of labelled ^{15}N as NH_3 was detected. Under field conditions, no added $^{15}NO_3$-N was lost until a heavy rain saturated the soil in the undrained columns. Soil columns in fallow and with wheat lost 25 percent of

the ^{15}N added by denitrification during this rain-saturation. Preventing the soil saturation by the excessive rain resulted in only 6 percent unaccounted-for N after analysis of the soil and plants.

In dryland cropping of central Nebraska, Ramig and Smika (1964) reported that recoveries of the fertilizer N by wheat, sorghum, and corn crops after wheat were 17, 33, and 36 percent, respectively.

In dry-farming regions of Cache and Juab Valley in Utah that had been farmed for 25 and 40 years, Bracken and Greaves (1941) reported that the N removed in the crop accounted for only 28.7 and 33.9 percent, respectively, of that lost from the soil. Since they considered leaching and erosion were not important losses in these areas, they considered that the major part of the unknown loss occurred through volatilization.

Losses of N from Soil

Loss of N into the atmosphere through volatilization is a factor affecting the amount of fertilizer N utilized by crops. Allison (1966), in reviewing recovery of N applied to soils, reported that the chief channels of loss of unaccounted for N in normal agricultural practice are probably due to leaching, NH_3 volatilization, or gaseous N in the forms of molecular nitrogen (N_2), nitric oxide (NO), or nitrous oxide (N_2O).

Khan and Moore (1968) studied the losses of added N from some Alberta soils. The losses of applied N were measured by the difference between the "no N" and the "added N" treatments. They found that most losses were less than

one-third of the added N, the maximum loss being 84 percent from a loam soil to which $NaNO_3$ had been added. Most of the N loss was attributed to chemo-denitrification.

Soil water influences the N loss. Wagner and Smith (1960) found that soil moisture within the range from air dry to field capacity had little effect on the amount of N lost from the soils they studied having silt loam textures. However, for a clay soil, increasing the moisture content within this moisture range increased N losses. In greenhouse experiments, Spurgeon and Grisson (1963) had a N loss from nitrate applied to clay soil which was most rapid during the first 2 days after the soil was water-logged. The water-logged soil lost about 50 percent of the applied N during the first 2 days. The rates of N loss were rather consistent for the 2 to 12 days period and then decreased during the 12 to 16 days period. After 16 days all of the applied N had been lost. The nitrate content of the nonwater-logged soil remained nearly constant throughout the 16 day period.

Broadbent and Tusneem (1971) reported that growing rice effectively reduced the magnitude of such a N loss by N uptake.

Although losses of N by denitrification can be large and are often considered to be the major gaseous loss of added N, this study is primarily designed to evaluate losses of N by volatilization of N as NH_3. The remaining discussion will emphasize studies providing information on N losses by this mechanism.

NH_3 Volatilization from Soil Receiving N Fertilizer

Theory of NH_3 volatilization

Fenn and Kissel (1973) proposed a mechanism of NH_3 volatilization from NH_4^+ fertilizers applied to calcareous soils. When it is applied to the soil surface, the NH_4^+ compound will react with solid calcium carbonate ($CaCO_3$). As a result, ammonium carbonate, $(NH_4)_2CO_3$, will be formed as represented by the following general equation:

$$x(NH_4)_zY + nCaCO_{3(s)} \rightleftharpoons n(NH_4)_2CO_3 + Ca_nY_z \qquad (1)$$

where Y represents the anion with ammonium and n, x, and z are numbers dependent on the valences of the anion and cation to form balanced equations.

The final reaction product $(NH_4)_2CO_3$, also reported by Singh et al. (1970), is unstable and decomposes as follows:

$$(NH_4)_2CO_3 + H_2O \rightleftharpoons 2\,NH_3\uparrow + H_2O + CO_2\uparrow \qquad (2)$$

$$2\,NH_3 \overset{H_2O}{\rightleftharpoons} 2\,NH_4OH$$

The amount of NH_4OH formed at a given time depends on the solubility of Ca_nY_x and its rate of formation. If Ca_nY_x is insoluble, the reaction (1) proceeds to the right causing more $(NH_4)_2CO_3$ to form. If no insoluble Ca_nY_x is formed, no appreciable quantity of $(NH_4)_2CO_3$ exists.

When $(NH_4)_2CO_3$ decomposes, CO_2 will evolve from the soil solution at a faster rate than will NH_3 and additional OH^- will be produced causing an increase in soil pH. Consequently, these reactions cause the NH_3 loss to increase because of the following reaction:

$$NH_4^+ + OH^- \rightleftharpoons NH_4OH \rightleftharpoons NH_3 \uparrow + H_2O$$

The NH_3 volatilization depends on the resultant pH of the soil solution. The NH_3-NH_4^+ equilibrium is pH dependent; a higher pH favors the NH_3 form and greater NH_3 volatilization.

Rates of NH_3 loss from soils

The loss of N from soil as NH_3 is now recognized as a more important channel of loss in many situations than was formerly supposed. NH_3 losses probably are greater in soils of high pH, high temperature, large concentration of NH_4^+ fertilizers, fast evaporation losses of soil moisture, and soils with low cation exchange capacity (CEC).

The amounts of NH_3 volatilized following surface application of 112 kg of urea N/ha to bare, moist, acid fine sandy soils were, after 4, 7, and 15 days, 24.3, 33.0, and 34.1 percent of the N applied in the field (Volk, 1959). He concluded that NH_3 evolution was largely completed in 7 days, if moisture and temperature were not limiting. Ernst and Massey (1960) found that the maximum daily NH_3 losses from urea occurred during the sixth day of aeration from soils of pH 5.0 and 5.5, but during the fifth day from the soils of pH 6.0 to 7.5

Makarov and Dokuchayev (1960), determining the amounts of NH_3 evolved from peat-bog soil and sod-podzolic (sandy loam) soil, reported that NH_3 evolution would seem to depend on variations in the hydrothermal conditions affecting the ammonification processes and the evolution of NH_3 from the soil. He suggested that in determining NH_3 evolved from soil the exposure time must be 1-2 hours. But when the rate of NH_3 evolution from the soil is very high, for example when

NH_4 fertilizers are applied to the soil, the exposure time must be reduced to about 1 hour. He found the rates of NH_3 evolved from the soil during the growing period varied in dried peat-bog soils and sod-podzolic medium clay loam soils from 0.0 to 25 g of NH_3/ha/hr. In the field, three times as much NH_3 was liberated during the daytime as at night from plots receiving urea applied to soil surface (Makarov and Ignatova, 1964).

Meyer et al. (1961) evaluated the evolved NH_3-N following application of 112 kg N/ha in different N sources to silty clay loam of pH 7.8 and different treatments: (1) with straw residue over surface, (2) wet to field capacity before broadcast application of fertilizer, and then incubated at 24 C. They found that most of the NH_3 evolution occurred in the first 4 days after application. Overrein and Moe (1967) reported that the highest rate of NH_3 loss occurred 2 days after all levels of urea application. The order in magnitude of loss from greatest to least loss was at 2 days, 3 days, 4 days, 5 days, and 1 day after application. Misra and Singh (1972) reported some NH_3 volatilization even after 28 days but the rapid loss was in the first 2 days.

Harding et al. (1963) compared volatile NH_3 losses from various nitrogeneous fertilizers that were broadcasted and remained on or near the wet surface of a silt loam (pH 7.7). The maximum rate of NH_3 loss (0.46 kg/ha/hr.) occurred within the first 6 hours of application of $(NH_4)_2SO_4$ and then diminished gradually to a constant of approximately 0.07 kg/ha/hr after 150 hours (6.25 days). This rate of loss continued through the second week, dropping only slightly by the fourteenth day.

Movsumov (1969) observed that when $(NH_4)_2SO_4$ was applied to soil containing 5.7 percent of $CaCO_3$, incubated at 30C, and with a moisture content 60

percent of the "full moisture capacity," the NH_3 loss doubled during the first 6 hours. The accumulative loss totaled 13.6 percent on the fifth day and 40.4 percent on the twentieth day but it was only 41.4 percent on the thirtieth day. A similar pattern of NH_3 loss was noted in his field experiments in which urea was added. According to Getmanets (1972), the loss of NH_3 was greatest during the first few days after the experiment was started when fertilizers were applied at the surface, especially at the high application rate (> 80 kg N/ha). The rates of NH_3 loss from urea 3, 7, and 14 days after application of 80 kg N/ha were 6.5, 6.8, and 0.6 g/ha, respectively, during a 2 hour measurement period. The corresponding figures for $(NH_4)_2SO_4$ were 4.8, 0.6, and 0.5 g/ha, respectively. Chao and Kroontje (1964), passing water-saturated air or water-unsaturated air over the soil surface receiving NH_4OH, reported that the rates of NH_3 volatilization from clay decreased with increasing time.

Overrein (1968) and Mahendrappa (1969) reported that the highest rate of NH_3 volatilization was exhibited on the third day after urea application to forest soils, this maximum was followed by a steady decrease in the rates with longer time. Watkins et al. (1972) observed approximately 80 percent of his measured NH_3-N loss during the first 5 days. Mills et al. (1974) found that most of the NH_3-N loss occurred on the first and second days following addition of NH_4Cl solution to the surface of a fine sandy loam soil. Nearly two-third of the NH_3 loss occurred during this period.

Musa (1968) studied NH_3 volatilization losses following surface application of urea and $(NH_4)_2SO_4$ to heavy, alkaline and calcareous soils. He found that

the highest rate of NH_3 loss occurred during the first week at all rates of N application and thereafter gradually decreased to low values. The lowest value was obtained in the sixth week. Volk (1961) also reported that NH_3 loss was largely complete within 7 days after application of urea, if moisture and temperature were not limiting. NH_3 loss by 24 hours was 74 percent of the total NH_3 loss in 100 hours after $(NH_4)_2SO_4$ application according to Fenn and Kissel (1973). The highest rates of loss from $(NH_4)_2SO_4$ and NH_4NO_3 for the first 6 hours were 3.0 and 0.5 percent per hour of added N.

Some factors affecting NH_3 volatilization from soils

Soil reaction. Soil reaction (pH) plays an important role in the amount of NH_3 that volatilizes from N fertilizers applied to soils, especially in alkaline and calcareous soils. Ammonical fertilizer will react readily with carbonates in the soil. The resulting $(NH_4)_2CO_3$ breaks down into NH_3 and CO_2. A theory of the process of NH_3 loss has been detailed by Fenn and Kissel (1973).

A number of investigators have studied the effects of pH on NH_3 volatilization. Jewitt (1942) measured the NH_3 loss from $(NH_4)_2SO_4$ applied to moist soils having natural alkaline pH values as the soil dried approximately to an air dry state. The NH_3 losses were 0, 13, 13, and 87 percent of added N at pH 7.0, 8.6, 9.3 and 10.5, respectively. Martin and Chapman (1951) measured losses of 9 to 51 percent of the N added in the form of NH_4OH when it was added to soils ranging in pH from 4.5 to 8.0. Very little NH_3 was lost at pH below 7.2 from added $(NH_4)_2SO_4$ and NH_4NO_3. Their results indicate that the pH of the soil is an

important factor in determining the loss of NH_3.

According to Wahhab et al. (1957), $(NH_4)_2SO_4$ in solution applied to sandy soil of initial pH 8.3 and sandy loam of pH 8.4 lost 27 and 13 percent of the added N in 6 days, respectively. When the soils' pH was lowered to 7.3 and 5.4 by adding $Al_2(SO_4)_3$, the amounts of NH_3 lost in 6 days at pH 5.4 and 7.3 were 0.0 and 9.1 percent for the sandy soil and 0.0 and 5.0 percent of added N for the sandy loam soil, respectively. Thus a pH drop from 8.3 and 8.4 to 7.4 greatly reduced NH_3 loss and a drop to 5.4 results in no loss. However, Volk (1959) observed that NH_3 loss even in acid soils occurred to a small extent. Gaseous loss of NH_3 during 7 days following surface application of $(NH_4)_2SO_4$ at rates of 112 kg N/ha to the wet fine sandy soil of pH 4.4, 5.4, and 6.3 were 0.1, 0.2, and 0.7 percent, respectively.

Wahhab et al. (1960) studied the loss of NH_3 from urea application during 5 drying cycles. The NH_3 losses from sandy soil of pH 4.6, 5.5, 7.0, and 8.5 were 2.0, 4.8, 11.8 and 20.2 percent of added urea N, respectively. Corresponding values for sandy loam were 3.4, 11.1, 21.6, and 39.1 percent, respectively. It is evident that NH_3 loss increases with increasing soil pH.

A recent study of Fenn and Kissel (1973) confirmed the effect of soil pH on NH_3 volatilization. They observed that the fluctuation of soil surface pH after N fertilizers were applied supports the NH_3 loss mechanism. For example, after surface application of NH_4F, $(NH_4)_2SO_4$, and NH_4NO_3, the soil pH rapidly altered from 7.7 to 8.9, 8.1 and 7.1, respectively. The corresponding rates of NH_3 loss for the first 6 hours were 11.1, 3.0, and 1.8 percent of added N,

respectively. The rate of soil pH change was somewhat similar to the rate of NH_3 loss. Soil pH can affect NH_3 loss even in flooded soil (MacRea and Ancajas, 1970). They observed that the initial pH of the soil was the soil characteristic mostly related to the magnitude of NH_3 loss from submerged soils.

Many other investigators also have reported that increasing soil pH caused an increase in NH_3 loss (Ernst and Massey, 1960; Filimonov and Strelnikova, 1974; Hutchinson and Scarsbrook, 1964; Mills et al., 1971; Mills et al., 1974; and Watkins et al., 1972).

Effects of carbonate content. Soil $CaCO_3$ content levels affect NH_3 volatilization. The amounts of NH_3 loss from N fertilizers added to the soil increase with increasing carbonate content. Carter and Allison (1961) observed NH_3 losses from added $(NH_4)_2SO_4$ of up to 15 percent on acid soil limed to pH 6.7.

Larsen and Gunary (1962) studied NH_3 losses from the mixtures of an acid soil (pH 4.5) and the carbonates of calcium (Ca), barium (Ba) or magnesium (Mg) when mixed in the proportions of 1 part carbonate to 10 parts of soil by weight. Soil mixtures with $CaCO_3$ and $MgCO_3$ lost more NH_3 from added $(NH_4)_2SO_4$ than from NH_4NO_3. With added $BaCO_3$, soil lost more NH_3 from NH_4NO_3 than from $(NH_4)_2SO_4$. This was explained as a result of $BaSO_4$ being precipitated on the surface of the $BaCO_3$ reducing the NH_3 loss as a result of reducing the solubility of the coated $BaCO_3$. However, their result is contrary to the theory of NH_3 loss proposed by Fenn and Kissel (1973) as mentioned before. Fenn and Kissel found that more NH_3 was lost in their

studies from soil treated with $BaCO_3$ than from those treated with $MgCO_3$ during 7 hours after $(NH_4)_2SO_4$ was applied to treated soil surface.

The work of Movsumov (1969) gave very interesting data about NH_3 losses on limed acid soils. After applying $(NH_4)_2SO_4$ to untreated soils that initially contained 0.0, 3.5, 5.0, and 7.1 percent $CaCO_3$, the losses of NH_3 after 10 days were 2.5, 9.9, 12.8, and 18.0 percent of added N, respectively. He found that adding $CaCO_3$ to noncalcareous soil at the rates of 0.0, 0.5, 1.0, 2.5, 5.0, 10.0, 20.0, and 30.0 percent caused losses of NH_3 of 1.5, 1.6, 4.0, 9.5, 14.8, 15.4, 18.0, and 18.0 percent of the added N, respectively. He concluded that the more $CaCO_3$ there is in the soil, the higher is the NH_3 loss. Five percent $CaCO_3$ caused an NH_3 loss 3.5 times greater than when 1 percent $CaCO_3$ was added. However, there were no differences with further increases in the amounts of $CaCO_3$ added. Feagley and Hossner (1975) also reported that substantial losses of the NH_3 from applied N may occur from limed acid soils.

Losses of NH_3 following application of 112 kg of urea N/ha to turf averaged 29 percent from unlimed turf, but 39 percent from limed turf (Volk, 1961). Respective losses on the same turf treatments using $(NH_4)_2SO_4$ were 0.4 and 19.7 percent, and applied NH_4NO_3 were 0.3 and 3.4 percent. Other investigators have also reported the losses of NH_3 were greater as the amounts of lime in soils increase (Filimanov and Strelnikova, 1974; Gasser, 1964; and Moe, 1967).

Effects of temperature. Temperature and soil moisture content affect NH_3 volatilization, but definitive studies have been few and difficult to do. Generally,

it is very difficult to maintain the temperature and moisture inside an enclosed chamber at the same values as the outside (open) environments when the field system is subject to sunlight. Most NH_3 loss experiments have been carried out in the laboratory at room temperatures with or without the losses of soil moisture during the period of experiment. McGarity and Rajaratnam (1973) reviewed the various equipment devised by various workers for measuring N losses as gaseous forms, including NH_3 loss in the field and simulated field environments. Hoult et al. (1974) modified some of the apparatus in order to control air temperature in the chamber as close as possible to the outside temperature by using a cooling system. Later Fernando and Roberts (1975) improved an air exchange system for studying NH_3 losses in both the laboratory and in the field. But they did not mention the problem of water condensation inside the system and the difference in temperature inside and outside the system. The high solubility of NH_3 in water makes water condensation critical.

Temperature effects on NH_3 losses have been recognized for years. Increases in temperature usually enhance NH_3 volatilization. Wahhab et al. (1957) measured NH_3 losses from $(NH_4)_2SO_4$ applied to samples of alkaline soil incubating at constant temperatures of 35 and 45 C in a water bath for 6 days. Losses of NH_3 from sandy soil at 30 and 45 C were 15.2 and 39.8 percent, respectively. Corresponding values obtained from applied urea were 29.3 and 39.1 percent (Wahhab et al., 1960).

Volk (1959) applied urea to the surface of a bare moist soil and measured the NH_3 loss. The magnitudes of NH_3 losses from sandy loam (pH 4.4) in 7 days

at 7, 16 C, and room temperature (about 22 C) were 0.4, 16.3, and 26.7 percent, respectively. Similar patterns were reported by Ernst and Massey (1960); accumulative NH_3 losses from applied urea for a silt loam soil (pH 6.5) at constant temperatures of 7, 16, 24, and 32 C were approximately 6, 9, 14, and 23 percent, respectively. The greater amounts of NH_3 losses at higher temperatures are attributed to the higher rate of urea hydrolysis and subsequent loss of NH_3 (Chin and Kroontje, 1963). Hutchinson and Scarsbrook (1964), found NH_3 losses at 4 and 32 C from added urea were 6 and 40 percent, respectively. Gasser (1964), considering an overall average of the forms of fertilizers and methods of applying them, concluded that more NH_3 was lost from a calcareous loam soil (39 percent $CaCO_3$) at 25 than 5 C.

Watkins et al. (1972) applied urea at rates of 224 kg N/ha to a Northwestern soil under forests and incubated the soils at 7 and 18 C for 30 days. NH_3 losses from small-pelleted urea at 7 and 18 C were 22 and 35 percent, respectively. Their work showed that NH_3 losses increased with increasing temperature at all urea pellet sizes studied (from 0.5 cm to 1 mm in diameter).

Fenn and Kissel (1974) found that the total NH_3 losses were only slightly influenced by temperature when applying precipipate-forming ammonium compounds such as $(NH_4)_2SO_4$. However, increasing the temperature did increase losses of NH_3 from non-precipitate-forming ammonium compounds such as NH_4NO_3. The losses from applied NH_4NO_3 at 12, 22, and 32 C were 14, 18, and 26 percent respectively, regardless of the rates of N applied.

Other experiments showing the effects of temperature on NH_3 losses have been reported by Martin and Chapman (1951), Nelson and Uhland (1955), Justice and Smith (1962), and Overrein and Moe (1967).

Effects of moisture. Jewitt (1942) reported that there was a close relationship between the loss of NH_3 and the loss of water. Loss of NH_3 ceased when there was no loss of soil moisture. Similar results were found by Ernst and Massey (1960), Justice and Smith (1962), Martin and Chapman (1951), and Wahhab et al. (1957). However, whether or not NH_3 loss occurs may be affected by the methods of experiments. For instance, Bremner and Douglas (1971) and Prasad (1976) found that NH_3 losses exist up to a 21 day period at almost constant moisture content. (They found only less than 0.15 ml of water was lost at the end of their experiments).

The soil temperature and rate of air flow through the soil surface affects rates of moisture loss and NH_3 losses, as well. Kresge and Stachell (1960) studied the effect of initial soil moisture contents on NH_3 losses from urea applied at the rate of 336 kg N/ha to the surface of a silt loam (pH 6.3); no attempt was made to maintain the initial soil moisture. The amounts of NH_3 volatilized in 10 days from soil with initial soil moisture contents of 0, 5, 10, 15, 20, and 30 percent (near field capacity) were 0, 2.7, 44.1, 83.4, 108.2, and 98.3 kg N/ha, respectively. It is evident that more NH_3 was lost from urea in soils drying out from near field capacity than from dry moisture conditions. Wahhab et al. (1960) reported that NH_3 losses from a sandy loam (pH 8.1) after five dryings from an initial soil moisture at each cycle of 0.25, 0.50, 0.75, and 1.0 times of its full moisture holding capacity (36 percent) were 23.0, 50.3, 55.2, and 60.8 percent, respectively.

However, the maximum NH_3 loss from $(NH_4)_2SO_4$ occurred at 0.25 times the moisture saturation capacity (Wahhab et al., 1957); with a further increase in soil moisture, volatilization of NH_3 was greatly reduced. Prasad (1976) reported similar results; NH_3 losses from S-coated urea, $(NH_4)_2SO_4$, and urea at both 22 and 32 C were greatest at 25 percent of the water-holding capacity of the calcareous clay soil. Sarigumba and Pritchett (1975) also reported that low soil moisture conditions favored NH3 loss from urea applied to soils under forests.

In contrast to the studies just reported, Chao and Kroontje (1964) found that NH_3 loss and water evaporation from soil follow different functions. The rates of NH_3 volatilization decreased with time, while the rates of water evaporation stayed almost constant to nearly air-dry conditions. Thus their results are not in agreement with that reported by Jewitt (1942) and Wahhab et al. (1957).

Makarov and Ignatova (1964) applied different forms of N fertilizers to a medium clay loam while maintaining the moisture content at 60 and 75 percent of the total moisture capacity (TMC) of the soil by periodic watering. The results showed that an increase in soil moisture content from 60 to 75 percent of the TMC increased the escape of NH_3 by a factor of 2 to 4. For instance, 0.03 mg of NH_3 was liberated after the addition of $(NH_4)_2SO_4$ to the soil (pH 5.0) having a moisture content of 60 percent of the TMC and 0.14 mg was released from the sample with a moisture content of 75 percent of the TMC. Increase in the NH_3 loss by increasing and maintaining higher soil moisture also was reported by Overrein and Moe (1967).

That the NH_3 loss is related to the initial soil moisture was also verified by the results of Gasser (1964); Hutchinson and Scarsbrook (1964); and Volk (1969).

The effects of soil texture, cation exchange capacity (CEC)and organic materials. Wahhab et al. (1957) reported that soil texture affected NH_3 volatilization. They applied $(NH_4)_2SO_4$ in solution to the soil in the laboratory. The total NH_3 losses for 6 days after N application from sandy soil (pH 8.3) and sandy loam (pH 8.4) were 20.2 and 10.2 percent of the added N. Although the greater loss measured by Wahhab and workers was from the sandier soils, Kresge and Satchell (1960) observed that NH_3 losses from applied urea were greater from a silt loam (pH 6.3) than that from a fine sandy loam (pH 6.5), regardless of the initial soil moisture content. NH_3 losses have also been inversely related to the soil exchange capacity (Allison, 1966; Hutchinson and Scarsbrook, 1964; Nelson and Uhland, 1955; and Martin and Chapman, 1951).

Gasser (1964) concluded that when 112 kg N/ha was applied as urea to soils with base-exchange capacity less than 10 me/100 g, more than 20 percent N may be lost as NH_3, the maximum losses decrease to 10 percent at 20 me/100 g, with less than 10 percent lost from soils of greater base-exchange capacity. Fenn and Kissel (1975) also reported that an increasing CEC of soil resulted in a decreased NH_3 loss.

Organic matter may affect NH_3 loss by altering the soil properties and activity but the effects are not clear. Gasser (1964) found that the least NH_3 was lost from an unmanured clay loam and the most was lost from an unmanured sandy loam. Applying farmyard manure in the field slightly increased NH_3 loss

from the clay loam but decreased considerably the loss from sandy loam. Applying farmyard manure in the field to the sandy loam increased the cation exchange capacity (CEC) from 7.8 to 12.4 me/100 g, which is in the range where NH_3 loss varies rapidly with changes in exchange capacity. By contrast, the CEC of clay loam increased from 18.8 to 23.4 me/100 g but in the region where NH_3 loss is less sensitive to change in CEC. Farmyard manure added to clay loam also increased organic matter which caused more rapid hydrolysis of urea and NH_3 loss.

Moe (1967) studied the effect of a corn mulch on NH_3 volatilization from a sandy soil after applying urea on the surface or incorporating it. Soil moisture was maintained at near saturation and the soil was incubated at 28 C for 9 weeks. Mulching decreased the NH_3 loss. The NH_3 loss was reduced by 24 percent when the corn was mixed in with the top 2.5 cm of surface soil before the surface application of urea. Mixing both the mulch material and the urea in with the top 2.5 cm of soil caused a 58 percent reduction in total NH_3 volatilization. Watkins et al. (1972) observed that NH_3 loss was greater when urea was applied to soil that was covered with forest floors than when urea was applied to bare soil. The differences in the NH_3 loss may be attributed to the factors governing urea hydrolysis. Adding some organic matter, such as filter press mud, reduced NH_3 losses regardless of the added N sources (Prasad, 1976). Changes in the soil CEC may also be a major cause.

Effects of ammoniacal fertilizer sources. Shankaracharya and Mehta (1971) applied different N fertilizers to the soil surface of a non-calcareous sandy soil (pH 7.2) in the field and measured the NH_3 evolution. They found that the

accumulative NH_3 losses from the soil when fertilizer was applied after irrigation varied in the order: urea (30.0 percent), groundnut cake (11.2 percent), diammonium phosphate (6.2 percent), calcium ammonium nitrate (4.6 percent), ammonium chloride (4.6 percent), ammonium sulfate (3.1 percent), ammonium sulfate nitrate (2.4 percent), and ammonium nitrate (1.8 percent) during 14 days. Among the most important factors affecting the variation of NH_3 losses are the dissociation or decomposition into ammonium ions, adsorption by soil colloids, and the effect of fertilizers on the pH of the soil.

Mosumov (1969) reported that NH_3 losses in the laboratory from soil (5.7 percent $CaCO_3$) receiving urea, $(NH_4)_2SO_4$, and NH_4NO_3 were 17.0, 15.4, and 9.8 percent during 10 days. Similar losses occurred in field studies. Although in this study the greater loss of NH_3 occurred from urea, Gasser (1964) had greater NH_3 losses in 40 days from $(NH_4)_2SO_4$ (9.6 percent) than from urea (6.8 percent) when they were applied to high calcareous flinty-loam soil (39 percent $CaCO_3$). Similar results were reported by Musa (1968).

Harding et al. (1963) measured NH_3 loss from broadcasting N fertilizers on soil surface in field experiments and obtained NH_3 losses after 2 weeks of 52.6, 31.0, 5.3, and 4.0 percent from urea, $(NH_4)_2SO_4$, NH_4NO_3, and urea formaldehyde, respectively. Similar results were reported by Volk (1961). But Overrein (1969) reported that NH_3 volatilization from ammonium or nitrate forms added to acid soils under forests was nonsignificant.

The solubility of NH_4^+ fertilizers (reactant) is an important factor governing the loss of NH_3. Harding et al. (1963) reported that NH_3 loss from urea was

13.2 percent but only 1 percent from slowly solubilized urea-formaldehyde when both were applied to a silt loam at the rate of 448 kg N/ha. Prasad (1976) also found that the NH_3 volatilized from the slowly solubilized S-coated urea was less than that from urea or $(NH_4)_2SO_4$.

Larsen and Gunary (1962) reported that NH_3 loss after 9 days from $(NH_4)_2SO_4$ applied to sandy soil (pH 7.7) was 64 percent. Corresponding values were 39, 30, 30, and 9 percent from diammonium phosphate, monoammonium phosphate, NH_4NO_3, and magnesium ammonium phosphate, respectively. The small losses from the magnesium ammonium phosphate were due to its low solubility. Fenn and Kissel (1973) proposed that the solubility of the reaction products helps govern the amounts of NH_3 losses. Greater losses of NH_3 from urea, followed by $(NH_4)_2SO_4$ and NH_4NO_3 in acid, slightly acid and alkaline were reported by Kresge and Stachell (1960); Meyer et al. (1961); and Volk (1959). The ammonium sulfate forms more insoluble products than does NH_4NO_3.

Effect of fertilizer rates. The application rates of N fertilizers as they affect the loss of NH_3 have been investigated by many workers. Shankaracharya and Mehta (1971) found that the losses of urea N as NH_3 14 days after surface application at the rates of 2.8, 27.7, 276.9, 553.7, and 1107.7 kg N/ha were 0.0, 4.0, 44.5, 57.1, and 66.4 percent from sandy soil of pH 7.2. It is evident that the loss of NH_3 increases with increasing the rate of N applied. Hutchinson and Scarsbrook (1964) also found that the average loss at the 56 kg N/ha rate was 12 percent and at the 896 kg N/ha rate it was 38 percent of urea N applied.

The effects of CEC in holding NH_4^+ is reduced, relatively, by larger total addition.

Wahhab et al. (1957) found that NH_3 losses from a sandy soil treated with $(NH_4)_2SO_4$ were 15.2, 18.2, and 24.9 percent from soil receiving the fertilizer at the rates of 560, 1120, and 1680 kg N/ha, respectively. Corresponding losses from a sandy loam were 6.8, 9.6, and 13.4 percent. Total NH_3 losses from added $(NH_4)_2SO_4$ increased with increased rates of N applied, but the percentage losses of NH_3 were not affected by the application rates when NH_4NO_3 was the N source, regardless of temperature (Fenn and Kissel, 1974).

In contrast to the direct effects of application rates on percentage losses, increasing the amounts of N applied to alkaline soil increased the total quantity of NH_3 loss but did not appreciably affect the percentage lost (Martin and Chapman, 1951; and Musa, 1968). Similar results from slightly acid soil (pH 6.5) were found by Overrein and Moe (1967).

Effects of fertilizer placement. Effects of placement of the fertilizers at different depths in the soil on the NH_3 loss have been examined by many workers. Recently, Shankaracharya and Mehta (1971) applied urea at different depths before or after irrigation of non-calcareous loamy sand (pH 7.2). When the fertilizer was applied after irrigation, the amounts of NH_3 lost during 8 days were 40.2, 33.4, 18.1, 0.4, and 0.0 percent of added N from the application depths of 0.0, 1.25, 2.5, 5.0, and 7.5 cm, respectively. The losses from the application of N after irrigation were greater than that from application before irrigation. These results showed that there will be negligible loss of NH_3 from

urea if it is applied at least 5 cm below the soil surface after irrigation, or if placed at least 2.5 cm deep before irrigation. Ernst and Massey (1960) reported that although the difference in NH_3 losses from mixing urea with surface soil layers at different thickness was not striking, there was a definite trend of decreasing NH_3 losses as it was mixed with layers of soil of increasing depth (thickness). A decrease in the loss of urea-N as the depths of its placement increases was also reported by Fuller (1963); Meyer et al. (1961); Overrein and Moe (1967); and Wahhab et al. (1960).

Comparison of the methods of applying urea by broadcast and by mixing it into the soils was conducted by Gasser (1964) and Meyer et al. (1961). They reported that NH_3 losses were greatly reduced by mixing the fertilizer with the soil regardless of soil differences and the different forms of N fertilizers used.

Wahhab et al. (1957) added $(NH_4)_2SO_4$ to alkaline soil at the soil surface and at 1, 2, 3 cm depths. Total NH_3 volatilized from those placement depths were, for sandy soil, 26.3, 16.9, 12.7, and 11.0 percent, respectively, and, for sandy loam, 12.9, 7.5, 6.1, and 4.3 percent. Thus increasing the depths of placement of fertilizer reduces the loss of NH_3 significantly. Reducing NH_3 loss by incorporation of NH_4^+ compounds into the soil was also reported by Fenn and Kissel (1975). Decreasing the soil moisture increased the effectiveness of soil incorporation in reducing NH_3 loss.

Methods to reduce NH_3 losses

From the discussion in the previous sections NH_3 loss depends on many factors, such as soil properties, N sources, methods of N placement, and climatic conditions

which affect mainly moisture and temperature. In practice, practical reduction in NH_3 loss can be accomplished by increasing the depth of placement of N fertilizers into the soil, by adding organic matter or compounds to reduce soil pH, the presence of plant residue mulches, or using N fertilizers that are of low solubility or are resistant to enzymatic microbiological action.

Most organic mulches decrease loss of NH_3. Adding farmyard manure reduced NH_3 loss (Gasser, 1964). Lower NH_3 loss occurred when lime and urea were applied together on the surface of a corn mulch than when they were applied to bare soil (Moe, 1967). NH_3 loss can also be reduced by other organic matter addition, such as filter press mud, a byproduct of the sugar industry, as reported by Prasad (1976).

NH_3 loss from urea may be reduced by the addition of acidifying chemicals, such as H_3PO_4, H_3BO_3, NH_4Cl, or $NH_4H_2PO_4$. Kresge and Satchell (1960) added 30 percent NH_4NO_3 with urea and were able to reduce NH_3 loss 40 to 50 percent. Watkins et al. (1972) added 25 or 50 percent NH_4Cl with crystalline urea and reduced the NH_3 loss 40 and 74 percent, respectively.

In addition, NH_3 loss from urea can be reduced by the addition of phosphates, H_3PO_4, or H_3BO_3. Singh et al. (1970) reported that adding phosphates with $(NH_4)_2SO_4$ at a rate of 0.25 percent P_2O_5 by weight to alkaline soil in the forms of $AlPO_4$, $FePO_4$, or $Mg_3(PO_4)_2$ reduced N losses. The reduction of N loss was as in the following series: $Ca_3(PO_4)_2 > Mg_3(PO_4)_2 > FePO_4 > AlPO_4$. They explained the reduction in NH_3 loss to be the result of formation of stable ammonium phosphate compounds.

Mahendrappa and Ogden (1973) added urea along with phosphorus (P) in the form of triple superphosphate to acid forest-covered soil in the field and observed a lower NH_3 loss. The NH_3 loss was drastically reduced because the triple superphosphate lowered the soil pH. However, doubling the added P from 112 to 224 kg P/ha did not proportionately reduce the extent of NH_3 volatilization. Similar results have been reported by Filimonov and Strel'nikova (1974).

Nomik (1973a) observed that addition of 10 percent metaphosphoric acid or of sublimed sulfur to tableted urea did not reduce NH_3 loss on forest-covered soil. Yet, the addition of 5 percent by weight of a solution of concentrated orthophosphoric acid or a fine-crystalline orthoboric acid to urea, reduced NH_3 loss 50 percent during a 28-day exposure (Nomik, 1973b). Sulfuric acid can also be used to reduce NH_3 loss as reported by Filimonov and Strel'nikova (1974).

Fenn (1975) studied the influence of mixing low and high loss ammonium compounds on calcareous soils. He mixed either $NH_4H_2PO_4$ or NH_4NO_3 with $(NH_4)_2SO_4$. The results showed that the loss rate and total NH_3 losses were reduced. The mixture of 30 percent $NH_4H_2PO_4$ reduced NH_3 loss from $(NH_4)_2SO_4$ about 40 percent.

Plant covers also reduce NH_3 volatilization. Urea top-dressed on burmudagrass gave less NH_3 loss than that top-dressed on bare soil (Kresge and Satchell, 1960). The presence of corn seedlings reduced NH_3 loss by at least 60 percent in the alkaline soils studied and by lesser amounts in the acidic and neutral soils when NH_4Cl was applied as the N source, Mills et al. (1974).

Ammonium and Nitrate Movement and Loss from Soil

Effect of soil water on NH_4^+ and NO_3^- movement

Soil moisture flow plays the most important role in N movement in the soil. Many soil scientists have devoted years to the study of NH_4^+ and NO_3^- movement and losses from soil profiles. The amounts of NO_3^- moved or leached below the soil root zone are closely related to the amounts of water added or leached through the soil root zone.

Krantz et al. (1943) found that NH_4^+ was rather immobile in the soil but NO_3^- was found to move freely with the soil moisture. Steward and Eck (1958) studied the movement of surface applied NH_4NO_3 into a clay loam soil at the moisture equivalent and at 3-, 5-, 8-, and 15- atmosphere (bar) tension. The soil samples, incubated at constant temperature (18 C) and moisture for 14 days, were analyzed for NO_3^- at different soil depths. They found that at the moisture equivalent downward movement of NO_3^- progressed to a depth of 6.4 cm, and to 5 cm when the soil was at the 3- or 5- atmosphere tension, and to 3.8 cm at the 8- and 15- atmosphere tension. They also found in the field that NO_3^- movement down to the depth of 3.8 cm was significant 10 days after application of NH_4NO_3 to silt loam when wetted to its moisture equivalent.

Whitehouse and Leslie (1973) measured the movement of NH_4^+ from anhydrous ammonia, urea, and $(NH_4)_2SO_4$ applied at 5 cm depth to alkaline black clay at moisture content of field capacity. They observed that movement of NH_4^+ was mainly lateral and vertical upwards. The higher lateral mobility of anhydrous

ammonia (5 to 6.5 cm from the point of N applied) is attributed to gaseous diffusion on application.

Many researchers have studied the NH_4^+ and NO_3^- movements as related to the amounts of water added and passing through the soil profile. Results of the experiment of Ray et al. (1957) indicated that the migration of NH_4^+ was closely related to the movement of water. Bates and Tisdale (1957) found the movement of NO_3^- through soil to be very closely related to the quantity of water added and porosity of soil materials. A multiple regression equation was developed which permitted an estimate of the mean NO_3^- movement from a knowledge of the values of the two variables of water added and soil porosity. Jurinak and Griffin (1972) also reported that NO_3^- elution from silica sand was proportional to the volume of water eluted.

Nelson (1961) studied the movement of NH_4^+ and NO_3^- from different N sources that were banded in two row treatments with controlled irrigation in a potato field. The distribution of NH_4^+ or NO_3^- in the soil were similar from the applications of urea, $(NH_4)_2SO_4$, NH_4NO_3, and aqua ammonia. However, Lyakh (1973) found that the mobility of N varied with the particular fertilizers used. It was greatest in the treatment with ammonia water, followed by $(NH_4)_2SO_4$ and urea. Broadbent et al. (1958) reported that urea moved less rapidly than NO_3^- partly because of rapid hydrolysis to NH_4^+ and partly because urea itself is held by weak adsorption forces to the soil particles.

Results of Nelson's (1953) work indicated that under irrigated corn production NH_4^+ did not move more than 7.5 to 10 cm with application of 30 cm of irrigation

water; a moderate concentration of NO_3^- moved to 27 cm. But high concentrations of NO_3^- were found on the soil surface carried there by capillary water as water evaporated. He concluded from his experiment there is no advantage in side-placing, side-dressing, or split-applications over the broadcast and plowing method in fertilizing corn with NH_4NO_3 in fine sandy loam soil.

Nielson (1959, 1960) and Nielson and Banks (1960) reported that a large quantity of NO_3^- accumulated in the bed (ridge) of the rows at the 0 to 5.0 cm depth under furrow irrigation of 102 cm of water, but at the 15 to 30 cm depth under 69 cm of water by sprinkling. It appeared that by furrow irrigation no appreciable amount of NO_3^- was moved below the 59 cm depth. It is probable that the distribution of NO_3^- is different under a system of flooding or ponding irrigation. With such a system, NO_3^- losses through leaching could be considerable.

Effect of soil properties on N movement in soils

The movement and retention of NH_4^+ in the soil were closely related to both texture and CEC of the soil (Ray et al., 1957). Movement of NH_4^+ in a loamy find sand was predominately downward and lateral; but movement in a loam soil was nearly symetrical with slightly greater upward and lateral movement than downward movement. Movement of NH_4^+ in loam having a CEC of 34.2 me/100 g soil was nearly equal in all directions, and much smaller in magnitude than movement in a loamy fine sand having a CEC of 3.2 me/100 g soil. Boswell and Anderson (1964, 1970) observed the NO_3^- movement in loamy sand to be considerably greater than in a clay soil. Even with excessive rainfall (about 178 cm), most of the

N recovered 11 to 12 months after application was concentrated between the 46 to 122 cm depth with the largest accumulation occurring in the 61 to 91 cm layer. The mean movement of N in the loamy sand was consistently greater than that in the sandy clay loam. Tyler et al. (1958) observed that the over-all lateral and vertical diffusion of NH_4^+ appeared to be much greater in the coarse-textured soil.

Movement of NO_3^- from the surface of different kinds of clay-sand mixtures maintained at -5 C was influenced by clay types, kinds of exchangeable cation, and soil moisture contents (Moore, 1972).

Jurinak and Griffin (1972) reported that $CaCO_3$ can adsorb NO_3^- from solution. In the absence of $CaCO_3$, a 400 gm soil in a column reacted with about 34 percent of the added NO_3^-, when 1 mg NO_3^--N was added as $NaNO_3$. When 100 g $CaCO_3$ was added to 300 g soil, the reaction of NO_3^- to the soil in the column was increased by 62 percent. Nitrate adsorption in acid soils of Mexico and South America was observed by Kinjo and Pratt (1971a), and some volcanic-ash soils of southern Chili can also adsorb NO_3^- (Schalscha et al., 1974). Kinjo and Pratt (1971a) reported that NO_3^- adsorption increased as acidity of the suspension increased to about 3.5. A significant correlation was observed between the amount of NO_3^- adsorbed and the amount of amorphous inorganic materials extractable with 0.5 N NaOH. They (1971b) also found that Cl^- showed a slight preference for adsorption over NO_3^-, and $SO_4^=$ and $H_2PO_4^-$ were greatly preferred over NO_3^-. Increasing the concentration of Cl^-, $SO_4^=$ and $H_2PO_4^-$

will cause a decrease in NO_3^- adsorption. Thus, adding $SO_4^=$ and NO_3^- in the same column increased the rate of movement of NO_3^- (Kinjo et al., 1971).

NO_3^- detention by an aggregated silty clay was enhanced when applied fertilizer was equilibrated with soil water 1 week before flood irrigation (Balasubramanian et al., 1973). They reasoned that equilibration in the soil involved diffusion of NO_3^- into aggregate micropores where the NO_3^- was less susceptible to transport in the flowing water which flowed mostly through the macropores during and soon after irrigation.

Upward and downward movement of NO_3^-

Linville and Smith (1971) found that in drier years NO_3^- was concentrated in the upper horizon of the soil profile. With higher rainfall the NO_3^- was concentrated more deeply in the profile. Similar results were also reported by Fox et al. (1970) and Krantz et al. (1943).

Wetselaar (1961) reported that on a laterite red earth in northern Australia NO_3^- accumulated in the top inch of the soil during the dry season (April - October). The peak of accumulation was not at the surface but at the 2.0 to 2.5 cm depth. Above this depth the NO_3^- content decreased linearly towards the surface; below this depth the NO_3^- content also decreased. He concluded that the high NO_3^- content was due to capillary movement upwards of NO_3^- formed biologically in the subsurface during periods of adequate water content.

In soil wet to near field capacity, NO_3^- and moisture moved upward in winter (from warm to cold) and downward again in early spring (Campbell et al., 1970). The amount of NO_3^- movement was negligible in soil wetted only to the

wilting point. NO_3^- movement downward into the soil appeared to be appreciable from either a fall or winter application of KNO_3 to the soil surface (Moore and White, 1973). NO_3^- applied before the soil froze moved downward to a greater extent than when it was applied on frozen soil. NO_3^- increases were found to a depth of 30 to 40 cm in the experimental field plots.

Effect of water on NO_3^- leaching losses from the soil profile

In lysimeter studies on N movement and loss through the soil profiles, leaching losses were directly proportional to the amounts of water moving through the profile during the spring months (Olsen et al., 1970 and Owens, 1960). Losses ranged from 5 to 20 percent of the applied N from the low to high moisture rates. The amounts of fertilizer N leached out of the soil per 2.5 cm of water in excess of 30 cm ranged from 1 to 2 kg N/ha/2.5 cm.

A relationship between NO_3^- distribution and movement of NO_3^- in the field and the amounts of rainfall has been observed by many workers (Boswell and Anderson, 1964; Fox et al., 1970; Linville and Smith, 1971; Thomas et al., 1973; and Wagner, 1965).

Boswell and Anderson (1964) studied the rate and depth of movement of N applied as KNO_3 on fallow soil under field conditions. They found that almost all of the applied N was found in the 0-7.5 cm and 7.5-15 cm layers after 5 weeks during which 5 cm of rainfall occurred on a sandy clay loam and 4 cm of rainfall occurred on a loamy sand. Even with a high accumulated rainfall, appreciable amounts of N were recovered at the 91 to 183-cm depths of the

two soils 76 weeks after N was applied to the fallowed plots. Yet in areas of low rainfall (about 30 cm) during fallow-wheat culture in Turkish soil, Fox, et al. (1970) reported that NO_3^- leaching is of considerable magnitude during the moist season even when precipitation is as low as 10 cm. Wetselaar (1962) also reported that rainfall is the most important factor affecting the movement of the NO_3^- anion. The mean movement of the anions of NO_3^- and Cl^- was 2.7 cm for each 2.5 cm of rainfall. There was a high positive correlation of 0.95 between the mean movement and amounts of rainfall. Terry and McCants (1973) found that in a specific soil of North Carolina, leaching of ions was directly related to the amounts of percolating water. A concentrated fertilizer solution made from NH_4NO_3, KCl, $CaCl_2$, and $MgCl_2$ was applied uniformly to the soil surface at a rate equivalent to that in a fertilizer band of 112, 168, 11 and 11 kg/ha of N, K, Ca, and Mg, respectively, had been applied in 10-cm wide bands 107 cm apart. The order of leaching (mean movement) of the ions studied was $Mg^{++} > NO_3^- > K^+ = NH_4^+$. The greater leaching of Mg^{++} was in part explained by the low amount of Mg^{++} in the fertilizer solution in relation to the other cations. Therefore, much of the applied Mg^{++} would have remained in solution rather than becoming involved in cation exchange reactions.

Slow leaching of NO_3^- formed from soil organic matter on soil in northern Nigeria is attributed to the combined effect of adsorption onto positive charges in the textural B horizon, high rainfall intensities (light runoff rather than percolation), and the presence of cracks and channels in the soil, down which water will pass quickly without leaching the newly mineralized NO_3^-

(Wild, 1972). Accumulative NO_3^- and Cl^- losses from a swelling clay soil by 22 cm of drainage water for the period December 1971 through August, 1972 were 15 to 20 percent and 18 percent, respectively (Kissel et al., 1974).

Linville and Smith (1971) applied NH_4NO_3 at rate of 134 kg N/ha to continuous corn plots annually for 6 and 7 years on different soil types and found no evidence of movement deeper than 244 cm. The NO_3^- content of the lower layers was similar to the no-nitrogen treatments, indicating that any leaching loss was low. The work of Thomas et al. (1973) showed that a large amount of NO_3^- was lost from the 90 cm depth of a silt-loam under killed sod plots, whereas, no NO_3^- was lost from the conventionally-tilled sod plots. They also found that the loss was attributed to lower evaporation from the killed sod (or mulch) soil and deep percolation of water and NO_3^- through larger pores in the wetter mulched soil. Wagner (1965) also reported that there was a significant loss of NO_3^- through the subsoil in field plots receiving NH_4NO_3 at rates of from 224-448 kg N/ha. A high NO_3^- concentration was found at a depth of 90 and 120 cm during the first 2 years.

It is evident that the amount of water added and eluted through the soil profile will cause a directly proportional NO_3^- movement and leaching loss from soils. However, the results obtained by Raney (1960) are contradictory to the other reports. He studied the N leaching loss from the Lakeland sand soil in humid regions for 7 years and concluded that the amount of drainage water moving through the soil profile had little effect on losses of either bases or of N. However, the amount of N that leached out was closely associated with the content of bases

in the leachates. Nitrate leaching loss in a 389-ha watershed under citrus orchard cover in southern California were reported by Bingham et al. (1971). About 67 kg N/ha are leached annually. The source of NO_3^- is considered to be primarily from N fertilizers applied at the rate of 146 kg N/ha/year.

Takahashi (1968) applied labelled $(NH_4)_2SO_4$ and KNO_3 at 56 and 168 kg N/ha to sugarcane growing in a concrete drainage lysimeter. There was no marked leaching of N fertilizer, despite heavy rains. Some fertilizer N moved downward in the lysimeters, but the relative amounts were small. Uptake by plants was probably rapid.

In areas of continuous annual N fertilization, NO_3^- may accumulate and then leach out beyond the root zone. For instance, MacGregor et al. (1974) found that after 11 seasons of growing corn on untiled clay loam, considerable NO_3^- occurred to at least the 10 m depth.

Soil profile characteristic may control the extent of NO_3^- movement (Gentzsch et al., 1974 and Lund et al., 1974). Lund et al. (1974) concluded that the NO_3^- concentrations found in deep soil cores were influenced by the characteristics of the soil profile, such as duripans and texture, which influence NO_3^- concentration through their effect on nitrification, denitrification, and drainage water volumes. In Washington County, Washington, NO_3^- levels in the water beneath a soil profile with natric horizons at intermediate or deeper depths were greater than NO_3^- concentrations in deep soil levels of soils with natric horizons at shallow depths. In some soils the NO_3^- contents were related to recent fertiliza-

tion practices and animal activity (Gentzsch et al., 1974). Low NO_3^- concentrations, however, was generally found in soils with shallow natric horizons irrespective of past practices.

Although NO_3^- leaching losses occur generally in the regions of high rainfall or overirrigation, considerable quantities of NO_3^- can be lost from the soil in low rainfall areas. Graetz et al. (1974) applied NH_4NO_3 to fine sand which was planted to millet. The amount of rainfall and irrigation water during the growing season was only 46.3 cm. Approximately 45 percent of the added N was leached below 150 cm, which was the root zone depth of millet. Microbial denitrification would not occur because the soil is well-drained and has little biodegradable carbon (C) in the lower horizon.

Garwood and Tyson (1973) observed that NO_3^- leaching losses were minimal during the period of active growth of plants or growing season, because N fertilizer is rapidly utilized by plants. However, when high levels of N fertilizer were applied (500 kg N/ha) to grass, up to 143 kg N/ha was found lost to drainage under low rainfall. Similar results were reported by Herron et al. (1968) with a high rate of N fertilizer applied to a silty clay loam and a silt loam cropped to irrigated corn.

Power (1970) has presented a report dealing with NO_3^- leaching loss under dryland agriculture in the Northern Great Plains of North Dakota. NH_4NO_3 was broadcast annually at a rate of 67 kg N/ha to spring wheat-barley rotation grown on silt loam from 1960 through 1963. He reported that no increase in NO_3^- due to fertilization could be detected at any depth in the soil in the year

1967. It is indicated that leaching of NO_3^- below the root zone is not likely to occur for annual small grains. However, he mentioned that in a spring grain-fallow rotation, NO_3^- could move below the root zone of spring grain during the months the soil has no crop or is being fallowed.

Possible practices to reduce NO_3^- leaching losses

The extent of NO_3^- movement and leaching loss from the root zone depends on, among other factors, the amount of water passing through the soil and profile characteristics. Crop-soil management practices can also enhance or minimize NO_3^- losses.

Olsen et al. (1970) recommended that the methods to minimize NO_3^- leaching loss below the root zone should include (1) limiting rates of N fertilizer additions to that required by the crop, (2) reducing the number of crops that receive fertilizer N in the rotation, (3) maintaining a crop cover on the land, (4) growing deep-rooted crops, (5) limiting irrigation water to the amounts required by crops, and (6) adding P and K fertilizers for more efficient use of fertilizer N. Kemper et al. (1975) reported that banding a fertilizer in the ridge 10 cm higher than the furrow irrigation's water surface markedly retarded the downward movement of the fertilizer salt to depths below the root zone during over-irrigation.

Denitrification can control the NO_3^- accumulation in the soils. Arnimelech and Raveh (1974) added water to plots by sprinkling at a rate and frequency to avoid leaching. The watering kept the profile wet and induced anaerobic

conditions. During the first day, the content of NO_3^- in the 0-30 cm layer dropped from 460 to 80 ppm. NO_3^- reduction in the 0-120 cm soil depth was about 50 percent at 7 days. Adding decomposable organic matter also enhanced NO_3^- reduction. Koepf (1974) has discussed the influence of fertilizing and of cropping on NO_3^- leaching from soil in the corn belts. Manuring with farm-produced material is a dominating factor in reducing the NO_3^- load in the drainage water.

Parker and Kohl (1975) reported that ground-up corn cobs added at rates up to 40 tons/ha reduced NO_3^- concentration in the top 30 cm. He found that the amounts of NO_3^- became smaller as the amounts of C applied increased in the first year. In the second year, reduced NO_3^- concentrations occurred down to depths of 120-150 cm. Landua et al. (1975) also found that adding municipal sludge minimized NO_3^- leaching when liquid sludge was incorporated in the soil, especially where the sludge was buried in trenches.

Nitrification inhibitors can also reduce NO_3^- leaching loss from ammonical fertilizers. Swoboda et al. (1975) applied N-Serve to black clay in field plots. Their results indicated that N fertilizers with N-Serve slowed the rate of nitrification and thus reduced NO_3^- leaching. Banks et al. (1975) reported that S-coated urea or N-Serve added to urea really reduced the NO_3^- concentration, thereby the potential for NO_3^- leaching is substantially reduced.

Effects of N Fertilization on Wheat Growth and Production

One primary purpose in this study with nitrogen is to evaluate some aspects of N fertilization of winter dryland wheat. These sections, following a review of

N reactions in soils, are a review of studies related to N fertilization of winter wheat grown in dryland conditions.

NH_4^+ and NO_3^- nutrition of wheat

Some studies using wheat cultures have shown the effects of mineral N on the growth of wheat plants. Bayley et al. (1972) reported that the wheat cell utilized NH_4^+ very quickly in media containing both NH_4^+ plus NO_3^-, but its growth was equal whether in a media with or without NH_4^+. Nitrate reductase activity and glutamase dehydrogenase activity in the wheat cell did not vary significantly whether in the presence or absence of NH_4^+ media. Cox and Reisenauer (1973) grew wheat seedlings from the age of day 6 to day 19 in dilute liquid cultures. They found that the growth rates and yields of plants grown with NH_4^+ added to the root media which already contained adequate NO_3^- exceeded that of the plants grown in NO_3^- or NH_4^+ alone. Concentrations of added NH_4^+ higher than adequate amounts caused depressed yields. In the all-NH_4^+ system the growth rate was limited to less than the maximum potential by NH_4^+ toxicity; in the all-NO_3^- system, the rate of NO_3^- reduction was the limiting factor. Increasing rates of NO_3^- uptake by the wheat were associated with increasing rates of Ca, Mg, and K uptake. In contrast, increasing rates of NH_4^+ absorption decreased Ca and Mg uptake. They suggested that controlling the amount of nitrification could alter the proportions of NO_3^- and NH_4^+ absorbed, altering yields, and reducing the amount of N leached from the soil profile.

Wheat seedlings absorbed NH_4^+ more than NO_3^- when grown on a medium with both NO_3^- + NH_4^+ (Breteler and Smit, 1974). They found that nitrate

reductase activity was lower in the wheat tops than in plants growing in a medium having NO_3^- alone. This result suggested that NH_4^+ inhibited nitrate reductase activity.

The maximum accumulations of N by wheat leaves and culms were at boot stage and at heading, respectively (Lal and Sharma, 1973). The rate of N uptake generally decreased after heading, accompanied by an increase in N accumulation of the spikes. This indicates that N is translocated from other plant parts to the kernels of the spikes. N application increased yields and mineral N uptake in wheat plants and plant parts. Singh and Anderson (1973) found similar results. Plants continued to absorb some N from the soil until they matured. The amounts of N translocated from the leaves, stem, and chaff was nearly 50 percent of the total N accumulated by the whole plant at maturity. Kafkafi and Halevy (1974) also reported that the maximum absorption of N by semidwarf wheat occurred at the heading stage; two-thirds of the N was absorbed from soil layers between 40 and 80 cm deep.

Monem Balba et al. (1972) studied the N uptake by wheat from soil in pots and from labelled $(NH_4)_2SO_4$. Absorption of fertilizer N was mainly during the period from tillering to ear-emergence but was affected by the time of application. Early application of fertilizer N (at seeding) caused a great absorption to be from soil N; more than 50 percent of the plant N content at maturity was absorbed by the plant from the soil N during the period of growth from emergence to tillering. During the period from tillering to ear-emergence, absorption of

fertilizer N was significant. Low N absorption from both sources occurred during the period from ear-emergence to maturity.

Methods of N application

Generally, fertilizer N is applied at the time of seeding for convenience and time saving. The efficiency of N utilization depends on the properties of the soils and on climatic conditions. Although soil application of N fertilizers is widely used in wheat production, foliar N application has recently been investigated and may become one of the possible practical methods to increase yield and quality of wheat grain.

The efficiency with which wheat plants could utilize N applied either as a spray or as a solid top-dressing appear to be largely dependent on subsequent rainfall. Cooper (1974) reported that spray and solid-planting applications of urea and NH_4NO_3 significantly increased grain yield and protein content of wheat. The application rates from 45 to 90 kg N/ha did not cause significant differences in grain yields. Time of application of urea spray had no effect on grain yield, but protein content was increased by the later urea spray. The 45 kg N/ha rate was the most effective in foliar application. Filip'ev et al. (1973) found that the 5 percent urea solution gave the best results when the weather 10 days after spraying was hot and dry, but higher concentrations were equally effective in a cooler year. Vitreousness, the contents of protein, crude and dry gluten, flour strength, and bread loaf volume were maximal when urea spraying was done within 10 days after earing or at the milky stage. Gorshkov and Verevka (1973) suggested that early top-dressing with NH_4NO_3 together with foliar

spraying of urea at ear formation improves grain protein and gluten contents of a hard wheat.

Field experiments conducted by Jain and Agrawal (1973) indicated that a single spray of urea N is less effective than split applications of the same quantity of N. They found that two sprays applied 30 and 35 days after planting gave higher yields than sprays applied at earlier growth stages.

Soil application of N is more efficient than foliar applications in increasing yield parameters (Nerson and Karchi, 1972). In their pot experiment, N applied to the leaves had an immediate but relatively short-lived effect and raised wheat yields mainly by increasing grain weight in the main spike. On the other hand, N applied to the soil had a delayed but long-lasting effect and increased plant yield by additional higher-yielding early and late tillers. Alkier et al. (1972) also found that in a glasshouse experiment less than 1 percent N from NH_4NO_3, urea, or $(NH_4)_2SO_4$ was absorbed into the grain when given as a foliar application. Generally, over 30 percent of the N from these fertilizers was absorbed when applied to soil. For effective use of foliar applications, several applications, which are expensive, would be required.

Effect of N sources and time of application

Gabar Ahmed and Dafalla (1973) applied urea and $(NH_4)_2SO_4$ to wheat grown for three consecutive seasons and found that grain yield of wheat was significantly influenced by rates and times of application but both forms of fertilizers behaved similarly. Optimum economic yield was obtained with 34-45

kg N/ha with half of the N applied at sowing and the other half at the flagging stage. Later Ayoub (1974) reported that under the same climatic conditions and in calcareous clay soil, urea produced higher grain yield than did $(NH_4)_2SO_4$, nitrophoska, $Ca(NO_3)_2$, or ammonium sulfate nitrate, each applied at 70 kg N/ha. Maximum grain yields were obtained with the application of N at the tillering and jointing stages. This experiment was conducted under adequate irrigation. But under unirrigated experiments reported by Fried et al. (1975), ^{15}N applied at planting and tillering gave a higher percent N in grain than that applied in the latter stages. The differences in amount of N taken up from NH_4NO_3, urea, and $(NH_4)_2SO_4$ were small. Generally, N is more efficiently used when applied at tillering.

On highly calcareous alluvial soil, calcium ammonium nitrate increased yield of wheat and percent N in the grain as compared with urea, ammonium sulfate nitrate, and $(NH_4)_2SO_4$ (Gupta and Narula, 1973). In a pot experiment on a mixture of alluvial soil and sand, Atanasiu et al. (1971) reported that grain yields were greater with $(^{15}NH_4)_2SO_4$ than with $Ca(^{15}NO_3)_2$. Generally, N uptake was greater from $(NH_4)_2SO_4$ throughout all stages of growth and N uptake from $(NH_4)_2SO_4$ was about equally effective when applied at 29 and 65 days after planting.

Under sparse fall rainfall a single pre-sowing application of urea or NH_4NO_3 incorporated to a 8-10 cm depth by a rotavator was equal in effectiveness to a split application between the pre-sowing application and a top-dressing in early spring (Nikdov et al., 1975). They also found that an equal amount of fertilizer split into three applications resulted in lower yields and did not improve wheat

quality. About equal yields resulting from urea and NH_4NO_3 were reported by Vanik (1974). But NH_4NO_3 was more effective than urea in increasing Cu and Mo contents in grain.

In West Pakistan, Hamid (1972) found that $NaNO_3$ caused higher wheat production than did $(NH_4)_2SO_4$ on clay loam soil having a pH of 8.1. N applied at tillering was utilized most effectively. Splitting the N application to add parts of it at seeding, tillering, and the boot stages increased grain yield significantly.

Clapp (1973) reported that in North Carolina applying all the N as NH_4NO_3 at seeding on a clay loam was as effective for high grain yields and high test weights as was using split applications. The 112 kg N/ha applied in October (seeding) was sufficient for maximum yields. But on fine sandy loam soil grain yields were lower for the application in October compared to an application in February. In Maryland, Standford and Hunter (1973) found that spring application of $(NH_4)_2SO_4$ was more effective than fall application. Spring application also gave higher protein contents than fall application (Hunter and Stanford, 1973).

Spratt (1974) studied the effect of NH_4^+ and NO_3^- forms of fertilizer N in growth chamber and field experiments using $(NH_4)_2SO_4$, NH_4NO_3, and $Ca(NO_3)_2$ as N sources. He found that fertilizer N applied as NO_3-N when the grain heads emerged increased the percentage N in the grain more than when applied as NH_4-N. A split application using NH_4-N applied at sowing (with a nitrification inhibitor) to give maximum leaf and stem growth and NO_3-N applied later at the boot stage to increase grain protein level may be worth considering for producing

high yields and good quality grain. Cox and Reisanauer (1973) have also suggested this technique to increase yields of wheat.

Fertilization of wheat in dryland areas

Moisture and N are generally the main and interacting factors limiting wheat growth on dryland areas. A 4-year study of the relations between wheat yields and various edaphic, cultural,and climatic factors in the wheat belt of Southern New South Wales by Taylor et al. (1974) indicated that seasonal rainfall is the major cause of yield variation. They also found that under optimum rainfall conditions soil NO_3-N level restricted yields wherever the concentrations in the surface 30 cm of soil are below 20 ppm. Smika and Greb (1973) reported that maximum yields were obtained with 28 cm of soil water available at seeding time. At least 106 kg NO_3-N/ha in a 1.2 or 1.8 m profile at seeding time was needed to obtain wheat grain with 12 percent protein in the Central Great Plains. In these areas they also found that there was a correlation between protein content of wheat grain and both available soil water at seeding plus NO_3-N in the soil profile (R^2=0.86).

Soil and climatic factors influenced hard red spring wheat response to fertilizer N in southwestern Saskatchewan (Read and Warder, 1974). The variables that could be measured before seeding (stored moisture and soil nutrients) had the greatest influence on the response to added fertilizers. But rainfall during the growing season had a greater influence than stored soil moisture on the yield and protein content of grain of wheat grown on unfertilized plots.

N fertilization and its effect on water use efficiency by dryland winter wheat were reported by Brown (1971) and Singh et al. (1975). Brown (1971) applied NH_4NO_3 to winter wheat before seeding. Wheat was found to extract soil water largely from the upper 90 cm when no N was added. However, wheat extracted water to depths of 183 cm when fertilizer N was added. Stored soil water, rather than seasonal rainfall, supplied 30, 55, and 76 percent of the available water used by the plant to 183 cm when wheat received 0, 67, and 268 kg N/ha, respectively. From the results Brown concluded that N application increased yields, water use, and water use efficiency.

Spratt and Gasser (1970) studied the effects of different forms of N on wheat growth in the field and in pots in the glasshouse. They found that with adequate water, wheat produced the most dry matter (and grain) and contained the most N when supplied with NO_3-N. However, when water was short and wheat growth was limited, NH_4-N was as good as or better than NO_3-N. He suggested that in semiarid climates, NH_4^+ fertilizer for wheat may be as good as, or better than NO_3-N. In humid climates, however, NO_3^- materials may be better, provided it is not subject to heavy losses by leaching or denitrification.

In dryland grain production at North Dakota, Alessi and Power (1972) observed that grain yields for an 8 year period were significantly higher when supplied conventional NH_4^+ and NO_3^- sources than when fertilized with the slow-N-release material, urea-formaldahyde (nitroform). Also, residual N from urea-formaldehyde fertilization was less effective for subsequent grain production than residual N from NO_3^- and NH_4^+ forms. Other lower solubility

N sources, such as S-coated urea, were also found to be less effective than conventional fertilizer sources for small grain production in 48 states and in more than 50 countries for a variety of soils and climatic conditions (Diamond, 1975). That conventional NH_4^+ and NO_3^- sources of fertilizer N are superior to urea-formaldehyde for small grain production in semiarid regions was also reported by Alessi and Power (1973).

Knott (1974) reported that under Saskatchewan's dry climatic conditions, wheat cultivars differ greatly in response to N fertilizers. He found that the heaviest application of fertilizer (90-122 kg N/ha) did not produce significant increases in yield beyond those produced by the lower applications (45 kg N/ha). The most economical response of dryland winter wheat grain to added fertility on a Miles fine sandy loam in Texas was with fertilizer added at 30 kg/ha of both N and P (Mulkey, 1971). Povlov and Mineer (1974) found that in general, addition of 90 to 120 kg N/ha gave a high yield of protein-rich grain in the Soviet Union. They suggested, however, that a late N top dressing is unsatisfactory under conditions of dry soil and sparse stands of wheat.

Fertilizing winter wheat in Utah

Moisture and N are two important interrelated factors that limit crop production on dryland farms in Utah. Early work of Peterson (1943) showed that increased yields of winter wheat are obtained by the use of $(NH_4)_2SO_4$ or $NaNO_3$ when applied broadcast in the early spring on winter wheat. Nitrate forms may be more effective per pound of N than ammonium forms (Nielson and

Van Epps, 1960, 1966; and Peterson, 1943, 1952). This is probably a result of one or all of the following: (1) failure of the ammonium form to be moved by rainfall from the surface into the root zone; (2) inadequate utilization of ammonium or lack of oxidation to the nitrate form; and (3) loss of NH_3 by volatilization.

When moisture is favorable, wheat in most areas respond to N application with increased yields, protein contents, or both (Nielson and Van Epps, 1960, 1966: Peterson, 1952; Peterson et al., 1953). When the annual rainfall is less than 28 cm (11 inches), N fertilization will probably not produce profitable increases in yields. When the annual precipitation was near the lower limit for producing dryland grain or rainfall was below normal, N applications affect protein content more than yield (Nielson and Van Epps, 1955). Indications existed that no appreciable difference existed between sources of N or between times of application. The yields varied from a low of 6 bushels per acre to a high of 45 bushels. Protein content ranged from 8 to 17.4 percent.

At the Blue Creek Experimental Station in northern Utah there was a significant linear response to added N, but added phosphorus caused little measurable effect on yields (Nielson and Van Epps, 1966).

In the northern Utah counties of Box Elder and Cache, early spring applications have produced higher yields than have fall applications. This may be due to N losses from fall application. Greaves and Bracken (1946) emphasized that seasonal distribution of rainfall was more important than the yearly total. Asfour (1950), in analyzing the Nephi station data from 1908-1949, found that spring rainfall in the cropping season was the most important factor in crop production,

producing a correlation of 0.556 with yield, while the correlation between yield and annual rainfall was only 0.366. He also found that correlation with temperature did not improve the correlation. Nielson and Van Epps (1960) concurred with this observation by reporting that spring storms influenced yields more than did storms at any other time of the year.

For 25 years, a number of trials have included $(NH_4)_2SO_4$ and NH_4NO_3 fertilizer additions as treatments. Without exception, the NH_4NO_3 treatments have either been equal to or better than the $(NH_4)_2SO_4$ treatment. Placement of fertilizer with the seed at time of planting has produced yields either equal to or better than those obtained from broadcast applications. When broadcast is done in the spring, it can be satisfactorily done as early as mid-February or as late as mid-April, as long as the N is moved into the soil by spring storms (Nielson and Van Epps, 1966).

Van Luik (1975) found that N sources and treatments within sources were responsible for the large difference in mineral N measured in the 0-30 cm soil depth which was recoverable 3 weeks after treatments. The grain yield averages from wheat receiving 56 kg N/ha applied before and after seeding were 2088, 2040, 1816, and 1686 for NH_4NO_3, $(NH_4)_2SO_4$, $Ca(NO_3)_2$, and urea, respectively. Lower yields may be due to the higher initial mineral N losses for $Ca(NO_3)_2$ and urea. He also reported that the favorability of the moisture regime in the latter stages of growth may also affect the yield and protein content.

Statement of the Problem and Objectives

A review of the literature shows that low recovery of added N is believed to be attributed in considerable part to gaseous losses, especially in the form of NH_3 from calcareous soils following surface or shallow application. The amounts of losses depend on variations in environmental conditions, consequently these will regulate the efficiency of N recovery by crops.

In semi-arid or dryland farms a considerable amount of NH_3 loss may occur because of the higher soil pH, rapid soil moisture drying and higher temperature during the growing season. Less yield of winter wheat from fall application of N fertilizer may be due to NH_3 loss prior to the absorption by wheat.

These same soils of $CaCO_3$ content may have NO_3^- - N leaching loss during the period of frequent intensive rainfall or long period of snow melting in early spring. The information concerning NH_3 loss from fertilized soils, mineral N distribution in the soil profile, N movement, and N recovery by winter wheat are not adequate in order to predict the N fertilizer use efficiency. A review of the literature failed to clarify whether the N sources influence the yields, the mineral N distribution in the soil profile, or any N loss in the dryland farms in Northern Utah.

The objectives of this study, therefore, are:

1. To evaluate several N carrier as sources of mineral N to winter wheat and effect on yields of these carriers.

2. To measure the mineral N concentration patterns in the field soil profile through the growing season of winter wheat grown in the field.

3. To evaluate the patterns of N movement in the soil profile.

4. To measure the NH_3 loss under different environmental conditions after N fertilizer application for the soil at the Blue Creek Experimental Station.

MATERIALS AND METHODS

Experiment I. Effects of Nitrogen Sources on Winter Wheat Yields and Mineral Nitrogen in the Soil

The experimental field was located at the Blue Creek Experimental Station in northeastern Box Elder County, northern Utah. The soil of the experimental site has been classified as Parleys silt loam, 6 to 10 percent slopes, a member of the fine-silty, mixed, mesic family of Calcic Argixerolls. General characteristics of the Parleys series soils are that they occur in upland elevations from 1260 to 1680 m, are well-drained, have a moderate erosion hazard, and are in a 380-460 mm annual precipitation area with a frost free period of 110 to 130 days. Primary use of the soils is for nonirrigated small grains, with a nonirrigated land use capability unit designated as IIIe-U. The surface 15 cm of soil near the experimental site contains 0.10 percent N, 1.2 percent organic matter, 24 ppm $NaHCO_3$-soluble P, 291 ppm exchangeable K, EC of the saturated paste extract of 0.6 mmhos/cm at 25 C, 0.1 percent $CaCO_3$, and a saturated paste pH of 7.0

Water relations for this soil were characterized in a recent publication, Soil Survey of Box Elder County (1975). Permeability was found to be moderately slow, with a slow to moderate intake rate. The available water-holding capacity to a depth of 150 cm is 25 to 30 cm of water. Roots may penetrate deeper than 150 cm. Usually strong lime accumulation was found at about the 85 cm depth.

The annual average of 12 years of precipitation is about 370 mm, with the period of Experiment I (September 17, 1973 to July 18, 1974) having a below average value of 226 mm of precipitation and with the period of Experiment II (October 10, 1974 to August 8, 1975) having nearly average precipitation of 361 mm. Table I shows these data.

Table I. Mean monthly precipitation and monthly precipitation during the period of Experiment I (September 17, 1973 to July 18, 1974) and Experiment II (October 10, 1974 to August 8, 1975) at the Blue Creek Experimental Station, northern Utah.

Month	Precipitation[a] (cm)	Month	Precipitation[b] (cm)	Month	Precipitation[c] (cm)
January	3.05	January, 1974	4.65	January, 1975	1.65
February	2.46	February	2.18	February	2.54
March	3.05	March	1.14	March	7.19
April	2.95	April	3.81	April	3.05
May	3.30	May	1.02	May	4.98
June	4.80	June	1.02	June	2.54
July	1.73	July 18, 1974	0.13	July	4.34
August	2.39			August 8, 1975	0
September	5.28	Sept. 17, 1973	1.22		
October	3.02	October	1.52	Oct. 10, 1974	6.22
November	2.49	November	2.16	November	2.03
December	2.36	December, 1973	3.76	December, 1974	1.52
Total	36.88		22.61		36.06

[a]From 1963-1974; usually snow cover exists from December to April. Data collected by R. F. Nielson and R. L. Cartee.
[b]Data for Experiment I.
[c]Data for Experiment II.

This investigation was designed to study the effects of N sources on soil NH_4-N and NO_3-N during the growing season and on winter wheat yields. The field plan consisted of a randomized block design with 4 replications. Each replication had 4 treatments of N sources. The unfertilized plots were used as the control treatment. Fifty-six kg N/ha from $(NH_4)_2SO_4$, NH_4NO_3, or S-coated urea (39 percent N) were applied broadcast before the wheat seed was drilled. Some incorporation occurred by the seed drill action. Individual plots were 9.14 m (30 feet) long and 3.66 m (12 feet) wide. The distance between replications was 18.29 m (60 feet). The field plot layout and treatments are shown in Figure 1. Wheat was planted on September 17, 1973 and harvested on July 18, 1974.

Replication

I	II	III	IV
S-coated urea	Control	Control	NH_4NO_3
NH_4NO_3	$(NH_4)_2SO_4$	S-coated urea	Control
Control	S-coated urea	NH_4NO_3	$(NH_4)_2SO_4$
$(NH_4)_2SO_4$	NH_4NO_3	$(NH_4)_2SO_4$	S-coated urea

Figure 1. Experimental plot layout of Experiment I in the field.

Soil samples at depths of 0-30, 30-75, and 75-120 cm were taken using a screw auger. Each sample represented a plot consisting of cores obtained from 6 holes within that plot. Two cores each were taken from the furrow bottom, the middle of the ridge slope, and the top of the ridges of the corrugations formed by the seed drill. Samples were taken at least 50 cm from the boundaries of the plots to avoid the border effects. All samples were combined and mixed thoroughly in the field before transferring them to polyethylene bags.

The soil sampling dates were on October 5, 1973 (18 days after fertilizing); November 2, 1973; April 20, 1974; and May 18, 1974. These sampling dates are referred to as the October, November, April, and May samplings, respectively, for convenience. All samples were frozen immediately after reaching the laboratory.

Grain yields were measured from four sample areas of 0.9 m^2 each in each plot. The grain was threshed and weighed for yields from each plot.

Grain samples were stored in closed polyethlene bags at room temperature until analyzed for total N (Kjeldahl-N).

Soil samples were analyzed for mineral N (NH_4^+ and NO_3^-) by the steam-distillation method described by Bremner (1965). Each replicate topsoil sample was analyzed 4 times but below 30 cm single analysis was done on each sample. Nitrite nitrogen was assumed to be negligible in all of these analyses, and was not separately accounted for in this study.

The total N content in wheat grain was determined by using a Macro-Kjeldahl procedure as described by Bremner (1965) which is used in the Soil

Testing Laboratory at Utah State University. Briefly, the plant material was digested by concentrated H_2SO_4 and digestion mixture, which consists of anhydrous powder of sodium sulfate, anhydrous powder of copper sulfate, and powder of selenium metal. After digestion, the NH_3 was determined by the additions of concentrated NaOH solution (40-45 percent NaOH by weight) and zinc for smooth boiling distillation, and titration of the NH_3 trapped in 2 percent H_3BO_4 solution, using standard H_2SO_4. The indicator used was bromcresol green and p-nitrophenol solution and new coccine.

Raw N percentages calculated from the data provided by this Macro-Kjeldahl procedure were converted to protein percentages by using the conversion factor of 5.7 (times total N) for grain as recommended by the Association of Official Analytical Chemists (Horwitz, 1970).

Experiment II. Nitrate Movement in Soils Receiving Ammonium Nitrate and Planted to Winter Wheat

The study of NO_3^- movement was conducted on soil at the Blue Creek Experimental Station, Box Elder County, northern Utah. The soil at the experimental site is Timpanogos silt loam, 1 to 6 percent slopes, a fine-loamy, mixed, mesic family of Calcic Argixerolls. Runoff is medium, and the hazard of erosion is moderate. The soil is deeper and at a lower position adjacent to the Parleys silt loam used in Experiment I. Therefore, its general properties are similar to those of Parleys silt loam as described in Experiment I.

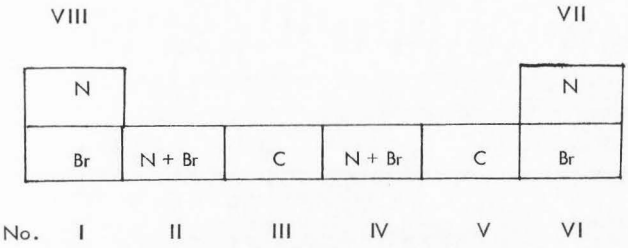
Usually this soil series is used for nonirrigated small grain. Its Land Use Capability unit is IIIe-U.

A duplicated plot design was set up to study the potential downward movement of NO_3^- and bromide (Br^-) in the soil profile. There were 4 plots with N and 4 plots with Br^- added. After winter wheat seed was drilled, on October 10, 1974, ammonium nitrate and potassium bromide (KBr) were broadcast at the rates of 400 kg N and 200 kg Br/ha, respectively. Bromide was used to estimate the maximum potential leaching of an anion such as nitrate because its occurrences are generally low (Bowen, 1966; Vinogradov, 1959), and bromide is not regarded as particularly toxic to plants (Martine, 1966). The use of bromide for following the potential path of nitrate movement through soil has been recently reported by Hargrove et al. (1972), Hargrove and Bausch (1975), and Smith and Davis (1974).

The individual plot size was 7 m long and 3 m wide. The field layout and treatments are detailed in Figure 2.

Before the applications of NH_4NO_3 or KBr, soil samples at 15 cm increments from 0 to 120 cm depth were taken from the control plots. Each sample was a composite of 4 cores.

After the material applications, the first soil sampling date was November 5, 1974. Soil samples were taken periodically using screw auger at depths of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 75, 75 to 90, 90 to 105, and 105 to 120 cm for plot No. II, III, IV, and V, but from 0 to 60 cm at 15 cm increments for plot no. I, VI, VII, and VIII. Samples within the depths of 0 to 30 cm, 30 to



Plot No.	Treatment (Materials applied)
I and VI	Br^- (KBr)
II and IV	N + Br^- (NH_4NO_3 + KBr)
III and V	Control (none)
VII and VIII	N (NH_4NO_3)

Figure 2. Experimental plot layout for Experiment II.

60 cm, and 60 to 120 cm were each composites of 10 cores, 8 cores, and 4 cores, respectively. Half of the total cores were taken in the top of the ridges and the other half in the corrugation bottoms. All samples were kept in polyethylene bags and frozen immediately after reaching the laboratory.

The second soil sampling date was May 28, 1975. Soils were sampled by taking four 150 cm cores from each plot with a hydraulic probe, and dividing them into the following increments: 0-15, 15-30, 30-45, 45-60, 60-75, 75-90, 90-105, 105-120, 120-135, and 135-150 cm. All samples were combined and

homogenized in the field before keeping them in polyethylene bags. Since observations on earlier samples showed no appreciable changes upon air-drying (Van Luik, 1975), samples were air-dried at room temperature, homogenized through a 2 mm sieve, and stored in the freezer room until N analyses were made.

Straw and grain yields of winter wheat were measured at the harvesting time on August 8, 1975. Each plot had 2 areas of 0.9 m^2 each harvested. The grain was threshed by hand and the total straw and grain yields were measured.

All soil samples were analysed for NH_4-N and NO_3-N using the method described by Bremner (1965), assuming NO_2^--N was negligible.

Straw samples, grain samples, and soil samples were analysed for total N by the Macro-Kjeldahl procedure as used in Experiment I. The brief procedure has been previously given in Experiment I. Percent protein contents of grain yield were estimated as described in Experiment I.

Bromide content was determined on air-dried soil samples. Twenty-five milliliters of 0.5 N K_2SO_4 solution was added to the oven-dry equivalent of 2.50 g of soil, shaken for 10 minutes, and filtered. The bromide content was measured using a bromide electrode.

The total N and bromide contents in the soil profile in ppm were converted to kg/ha by using the bulk density of the soil.

The precipitation occuring at the Blue Creek Experimental Station, northern Utah, during the time of the study was previously given in Table 1. The maximum, minimum, and mean air and soil temperatures at a 2.5 cm depth are shown in Table 2.

Table 2. Maximum, minimum, and mean air and soil temperatures at 2.5-cm depth at the Blue Creek Experiment Station.

Month	Air temperature,[a] C			Soil temperature,[a] C		
	Max	Min	Mean	Max	Min	Mean
January	10	-17	- 4	0	- 1	- 1
February	9	-15	- 3	- 1	- 1	- 1
March	18	- 9	5	19	- 3	8
April	21	- 5	8	21	0	11
May	28	- 1	14	29	2	16
June	31	5	18	36	8	22
July	33	11	22	38	14	26
August	32	8	20	37	13	25
September	28	1	15	31	7	19
October	23	1	12	25	2	14
November	17	- 4	7	15	2	9
December	10	- 12	- 1	1	- 2	- 1
Average	22	- 3	10	21	3	12

[a]Data from 1965 to 1968 and 1973 to 1975; collected by R. F. Nielson and R. L. Cartee.

Experiment III. Ammonia Volatilization from Soils Receiving N Fertilizers

The NH_3 volatilization from N fertilizers applied to soil was conducted mostly in the laboratory.

A Timpanogos silt loam was used for most of this study, but some other soils were used in certain studies. The 15 cm surface soil used was air-dried, ground to pass through 2 mm sieve, and well mixed.

A diagramatic sketch of the apparatus for collecting NH_3 volatilized from the soil is shown in Figure 3.

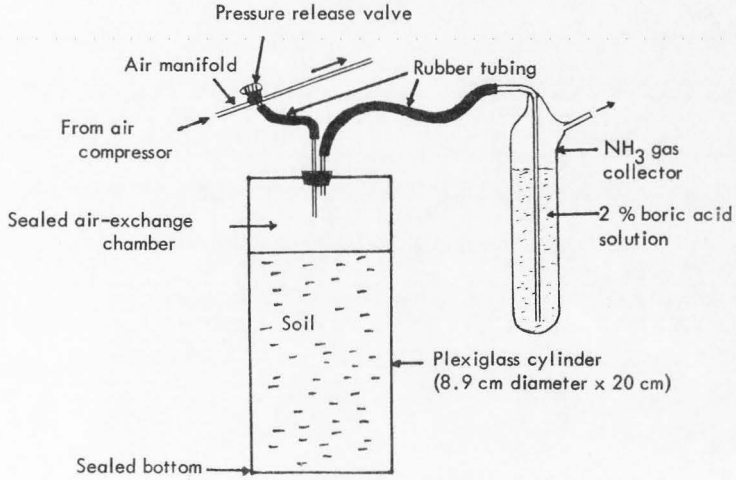


Figure 3. Diagrammatic sketch of apparatus used in determining NH_3 volatilization from soil.

About 1200 g of soil was mixed well and placed in a plexiglass cylinder having dimensions of 8.9 cm inside diameter by 20 cm long. The soil sample filled the cylinder to a height of about 15 cm; a 5-cm tall space was used as an air exchange chamber. The cylinder with sample was tamped gently on a lab bench to settle the soil. Distilled water equivalent to field capacity of the soil (23 percent) was slowly added by the use of a funnel touched to the inside wall of the cylinder to avoid the disturbance of the soil surface. The wetted cylinder was allowed to equilibrate for 24 hours before NH_3 volatilization experiments were started.

The rate of compressed air flow into the gas exchange chamber was adjusted by measurement to a flow rate approximately 1.2 liters of air per minute. Although no precise method of maintaining this rate of air flow was available, it was held as nearly constant as possible by adjusting the release valve and the visual estimate of bubbling rate which was periodically evaluated by flow measurements. The air flow should have replaced the gases in the air exchange chamber about 4 times per minute.

Evolved NH_3 was collected in a solution of 2 percent boric acid. The boric acid was titrated with standard H_2SO_4 using a mixed pH indicator of bromcresol green and p-nitrophenol, and the NH_3 content calculated. Checks on loss of NH_3 through the boric acid in the collector vessel by connecting several collectors in series indicated that no NH_3 escaped through the first collector if the rate of NH_3 loss was less than 5,000 μg NH_3-N per day. Essentially no measurable loss of NH_3 was observed when the soil was aerated

during the experimental periods without the addition of N fertilizer. Therefore, it was assumed that most or all NH_3 volatilized was formed from the N fertilizers added.

Modifications of some basic factors involved in the studies of NH_3 volatilization were given in each specific experiment.

Standard statistical procedures were used to aid in the interpretations of some experimental results and the significant differences between the treatments mentioned in the results and discussion were significant at the 0.05 level.

RESULTS AND DISCUSSION

Data from some of the individual replicates which are not tabulated in the text are shown in the Appendix.

Experiment I. Effects of Nitrogen Sources on Winter Wheat Yields and Mineral Nitrogen in the Soil

Environmental conditions prior to the soil sampling times in fall 1973

At the planting date on September 17, 1973, the soil surface was dry but the soil below the surface was moist due to 1.55 cm and 6.22 cm of precipitation on September 4 and 10, 1973. No soil temperatures were determined in September 1973. The averages of the maximum and minimum soil temperatures at a 2.5 cm depth for the years 1965 to 1968 and 1973 to 1975 were 31 C and 7 C. The amount of rainfall from September 17 (planting and fertilization) to October 5, 1973 (soil sampling date) was 1.22 cm. During this time wheat germination and root initiation occurred. Low evapotranspiration was assumed to occur during this period because of the general coolness.

The averages of the maximum and minimum soil temperatures in October 1965 to 1968 and 1973 to 1975 at the 2.5 cm depth were 25 C and 2C. In October 1973 the corresponding temperatures were 24 C and -3 C. The amount of rainfall from October 5 to November 2, 1973, was 1.52 cm. During October the wheat was in the early tillering growth stage.

Grain yield, protein content and N content in the winter wheat grain

The primary goal of N fertilization is to produce high yields and high quality grains by management practices which are agronomically sound, economically feasible, technically possible, and profitable to the growers.

Grain yields, protein contents, and N content in the grain of winter wheat grown at the Blue Creek Experimental Station in September 1973 to July 1974 are shown on Table 3. Nitrogen fertilization with NH_4NO_3, $(NH_4)_2SO_4$ and SCU increased the measured wheat grain yields but the increase was not significantly

Table 3. Grain yields[a], protein content, and N content in the grain yield of winter wheat grown from September 17, 1973, to July 18, 1974, at the Blue Creek Experimental Station. The soil received 56 kg N/ha from various N sources broadcast before planting.

N source	Grain yield[b] kg/ha	Protein content %	Grain N content in grain yield kg N/ha
Control	1990 a	9.33 a	32.2 a
NH_4NO_3	2292 a	12.20 b	49.0 b
$(NH_4)_2SO_4$	2290 a	12.08 b	48.3 b
S-coated urea	2322 a	11.08 b	44.5 b

[a]Grain yield and protein content were based on 70 C dried weight basis.
[b]Letters in each column followed by different letters are significantly different at the 0.05 level.

different from the unfertilized wheat yield. However, all three N sources increased the percentage of grain protein and N content in the grain significantly, according to statistical comparisons. All sources of N gave similar grain yields. These findings were in agreement with the report of Diamond (1975) which indicated that SCU had little or no advantage over soluble sources for small grains. Slightly lower protein content was found in the SCU plot. Other N slow-release fertilizers, such as urea-formaldehyde, have been found to be inferior to ammonium and nitrate forms in semi-arid or dryland grain production (Alessi and Power, 1972, 1973).

The patterns of mineral N in the soil profile with depths and sampling dates

Mineral N in the 0-30 cm soil depth on October 5. The mineral N in the 0-30 cm soil layer as a result of different N sources and at different soil sampling times are shown in Figures 4 and 5 (or Table 19). The soil temperature and moisture in September was favorable for soil N mineralization. The soil, classified as Argixeroll, has 1.2 percent organic matter in the surface horizon and a high base content. The mineral N in the 0-30 cm deep soil layer apparently increased considerably from the fertilizer applications of 56 kg N/ha of NH_4NO_3 and $(NH_4)_2SO_4$ during the 18 days after N fertilization. The values of mineral N of plots receiving NH_4NO_3 and $(NH_4)_2SO_4$ were 172 and 119 kg N/ha. The expected value if no acceleration of soil N mineralization was caused by added fertilizer was 106 kg N/ha (control value + added N). Corresponding mineral N value for SCU was 87 kg N/ha which was not statistically different from the

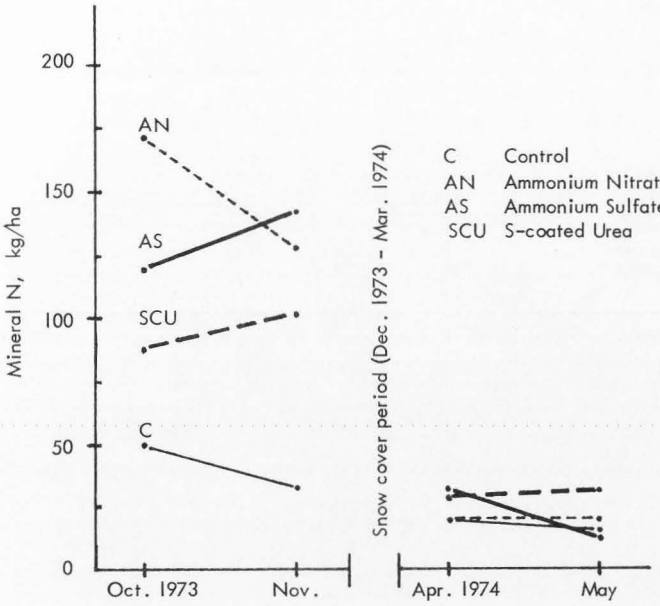


Figure 4. Mineral N (NH_4-N + NO_3-N) contents in the 0-30 cm depth of Parleys silt loam sampled at different times at the Blue Creek Experimental Station. The soil received 56 kg N/ha as different N sources broadcast before winter wheat was planted on September 17, 1973.

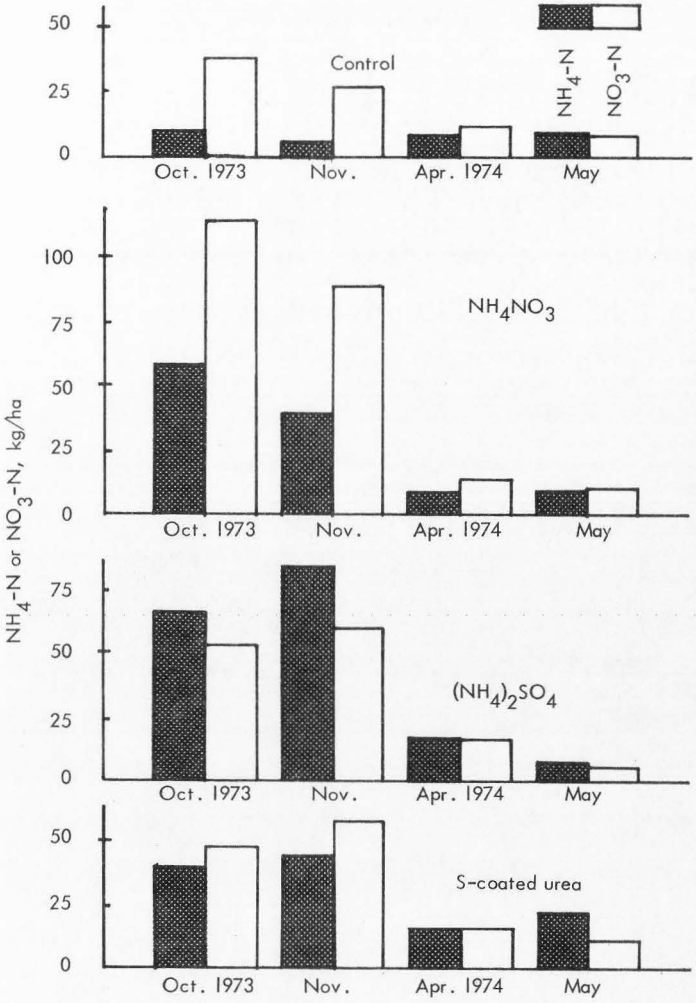


Figure 5. Contents of NH_4-N and NO_3-N in the 0-30 cm depth of Parleys silt loam sampled on various dates. The soil received 56 kg N/ha as different N sources broadcast before winter wheat was planted on September 17, 1973, at the Blue Creek Experimental Station.

unfertilized plots (50 kg N/ha). The values of mineral N of the individual replicates are shown in Table 4.

Table 4. The mineral N contents (kg N/ha) in the 0-30 cm soil depth sampled on October 5, 1973. The soil received 56 kg N/ha broadcast on September 17, 1973.

N source	Replication I	II	III	IV	Average†
Control	60	48	44	48	50 a
NH_4NO_3	234	182	75	198	172 c
$(NH_4)_2SO_4$	107	115	114	139	119 bc
SCU	68	103	72	103	87 ab

† Data followed by different letters are significantly different at the 0.05 level of probability.

The higher mineral N contents in the fertilized plots compared to unfertilized plots were attributed to both the fertilizer mineral N added and to accelerated soil N mineralization during the 18 days after fertilization before sampling the soil. The average moisture content in the 0-30 cm soil layer at the October sampling time was 16 percent. There was no way in this study to distinguish the N derived from mineralized soil N and that N from the fertilizer N.

Stimulation of soil N mineralization as a result of the addition of fertilizer N or salts (usually called priming effect) has been reported for studies done both

in the field (Westerman and Kurtz, 1973) and in the greenhouse and laboratory (Broadbent, 1965; Broadbent and Nakashima, 1971; Sapozhnikov, et al., 1968; and Westerman and Tucker, 1974). Increase in mineralized N of 52 percent (Broadbent, 1965) and 118 to 220 percent compared to those of unfertilized soil (Broadbent and Nakashima, 1971) are reported under laboratory conditions. Lower mineral N from SCU plot in early sampling periods might be due to the slow release rate of N and incomplete hydrolysis of urea-N to NH_4-N.

Ammonium N contents in soils receiving the three various N sources were similar. S-coated urea additions caused the lowest NH_4-N of the added N sources.

The ammonium nitrate plots in October had the greatest mineral N and the largest amount of NO_3-N. The increase in mineral N over that N content in other fertilized plots may be attributed to many factors, such as the nature of the salts added (Broadbent and Nakshima, 1971), an interaction between the soil and fertilizers or in the microbial activity differences. The exact mechanism by which enhanced mineralization is triggered is not experimentally proven. One explanation (Fenn and Kissel, 1973) is that the concentration of hydrogen ions in the soil surface receiving NH_4NO_3 is higher than that in soil receiving $(NH_4)_2SO_4$, when applied to calcareous clay soil of pH 7.6. The ammonium nitrate, by producing more hydrogen ions than $(NH_4)_2SO_4$ in the soil, increases N mineralization more than does $(NH_4)_2SO_4$. This hypothesis is only speculative.

Mineral N in the 0-30 cm soil depth on November 2. The moisture content of the soil on November 2 (46 days after adding fertilizers) was 14 percent and the soil temperature following October 5 was lower than that prior to October 5.

Figure 4 shows that soil samples fertilized with all three N sources yielded significantly more mineral N than did the unfertilized plots. Although there was not statistically significant change, the mineral N in NH_4NO_3 plots appeared to decrease between the first and second sampling dates, but appeared to increase in the plots treated with $(NH_4)_2SO_4$ and SCU. The amounts of mineral N of individual replicates are shown in Table 5.

Table 5. Mineral N contents (kg N/ha) in the 0-30 cm soil depth sampled on November 2, 1973. The soil received 56 kg N/ha broadcast on September 17, 1973.

N source	Replication I	II	III	IV	Average†
Control	48	24	40	20	33 a
NH_4NO_3	179	154	79	99	128 b
$(NH_4)_2SO_4$	154	158	142	119	143 b
S-coated urea	202	64	68	72	102 b

† Data followed by different letters are significantly different at the 0.05 level of probability.

Significantly higher NH_4-N occurred in plots receiving $(NH_4)_2SO_4$ than occurred in the other treatments (see Figure 5 or Table 19). Again, NO_3-N was the highest in plots treated with NH_4NO_3, although it appeared to decrease from 114 kg N/ha on October 5 to 89 kg N/ha on November 2. The decrease in NO_3-N may be due to immobilization. The NO_3-N concentrations in deeper soil depths were unchanged suggesting that no downward movement of NO_3-N occurred during this time.

The increased NH_4-N at the time of the November sampling might be due to the environmental conditions being more favorable for ammonification than for nitrification. Most investigators agree that at low temperature and moisture, nitrification is more retarded than is ammonification. Thus, NH_4-N could increase if mineralization was faster than nitrification and immobilization.

Mineral N in the 0-30 cm soil depth on April 20 and May 18, 1974. Snow cover existed from December to March. Therefore, N transformations during this period were presumed to be low. Figure 4 or Table 19 shows the mineral N content in the 0-30 cm soil depth of fertilized plots on the April 20 and May 18, 1974 sampling dates. The mineral N contents were much lower than those in the October 5 or November 2, 1973 sampling dates. In fact, they were not significantly different from mineral N contents in the unfertilized plots. All three N sources gave similar mineral N contents (Figure 5), although the SCU plot had slightly higher amounts in the NH_4^+ form than did other plots on the May sampling date.

It is obvious that 56 kg N/ha broadcast before planting in the fall did not increase the mineral N concentration measured in the spring of the following year. The lack of difference in the mineral N contents between the fertilized plots and unfertilized plots in April and May are possibly due to (1) the rapid absorption of N during the tillering stage in March and April, (2) the immobilization of N into organic forms in the soil, (3) denitrification, or (4) leaching losses. Results in experiments to be discussed later suggest that some leaching can occur. The first three processes should exist in all such conditions to some extent.

The higher NH_4-N in the SCU plots on the May sampling date is possibly due to slowly released N from residual SCU granules because of the more favorable moisture and temperature in late April and May. S-coated urea granules appear to be quite stable at soil temperature ranging from -1 C to 10 C (Kilmer, 1975). Therefore, the mineral N contents in SCU plots were slightly lower in April than in May due to the higher soil temperatures in May.

Mineral N in the 30-75 cm and 75-120 cm depths on various sampling dates. Figure 6 shows the mineral N contents in the 30-75 cm soil depth as a result of different N sources and different sampling dates. The corresponding N values for the 75-120 cm soil depth are shown in Figure 7. The relative amounts of NH_4-N and NO_3-N are shown graphically in Figure 8 for the 30-75 cm and in Figure 9 for the 75-120 cm soil depth.

There was no difference in the amounts of NH_4-N or NO_3-N in the 30-75 cm depth on any sampling dates among plots treated with NH_4NO_3, $(NH_4)_2SO_4$,

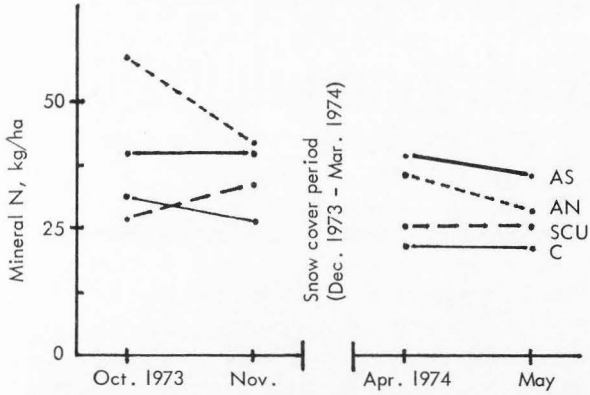


Figure 6. Mineral N contents in the 30-75 cm depth of Parleys silt loam sampled on four dates. The soil received 56 kg N/ha from different N sources broadcast before winter wheat was planted on September 17, 1973, at the Blue Creek Experimental Station.

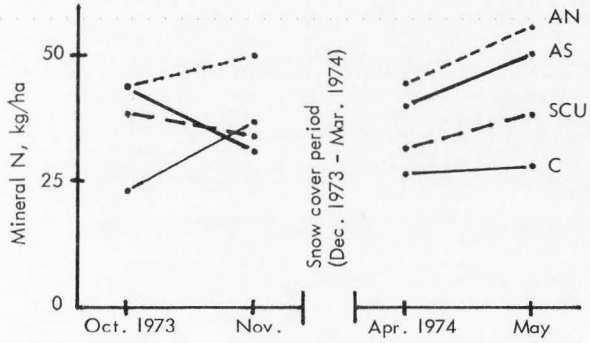


Figure 7. Mineral N contents in the 75-120 cm depth of Parleys silt loam sampled on four dates. The soil received 56 kg N/ha from different N sources broadcast before winter wheat was planted on September 17, 1973, at the Blue Creek Experimental Station.

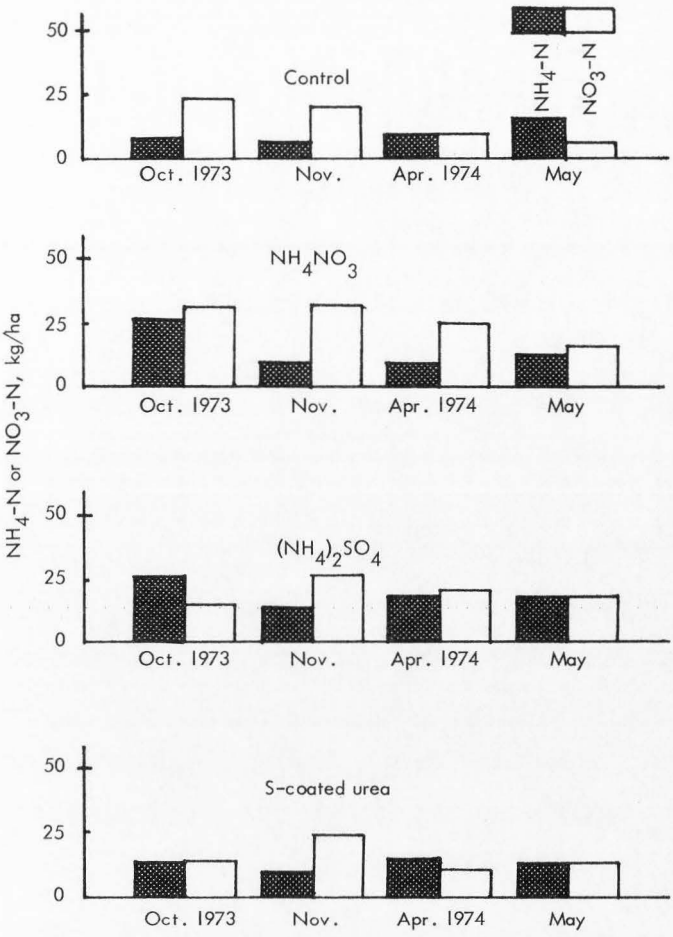


Figure 8. Contents of NH_4-N and NO_3-N in the 30-75 cm depth of Parleys silt loam sampled on various dates. The soil received 56 kg N/ha as different N sources broadcast before winter wheat was planted on September 17, 1973, at the Blue Creek Experimental Station.

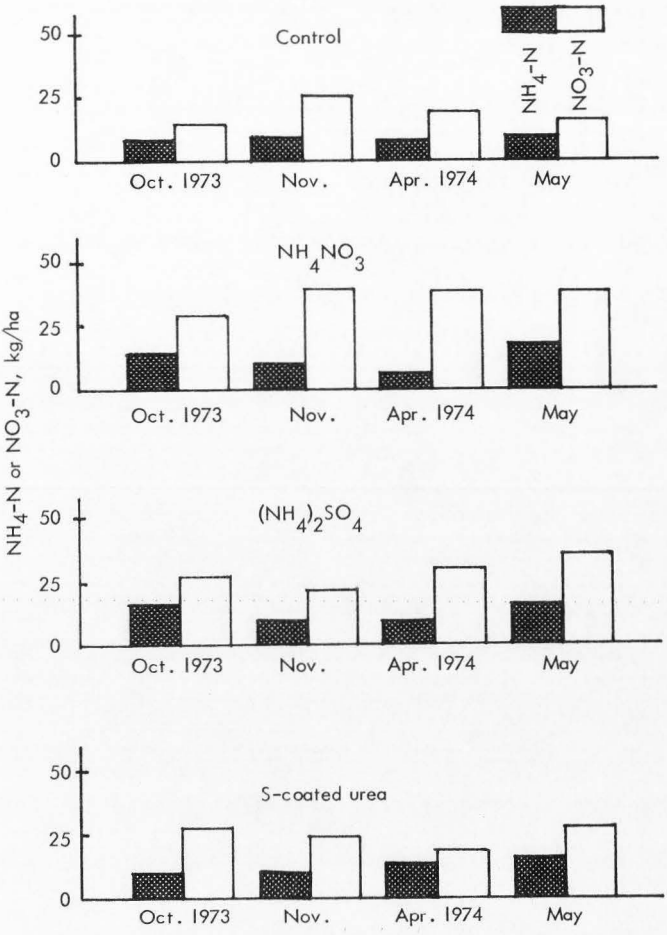


Figure 9. Contents of NH_4-N and NO_3-N in the 75-120 cm depth of Parleys silt loam sampled on various dates. The soil received 56 kg N/ha as different N sources broadcast before winter wheat was planted on September 17, 1973, at the Blue Creek Experimental Station.

and SCU. Similar patterns were found for the 75-120 cm layer. Data are given in Tables 20 and 21, respectively.

Although there was no change of the averages of the amounts of mineral N in the deeper soil layers of the N treated plots on any sampling date, the evidence of NO_3-N accumulation was observed in the hard pan layer of the replication I. On the May sampling date, the NO_3-N contents of the fertilized plots in the hard pan layer of the replication I were higher (ranging from 15 to 32 kg/ha/15 cm) compared to that of the other three replications (ranging from 2 to 13 kg/ha/15 cm). This evidence shows that there might be some amounts of NO_3-N moved down and accumulated in the hard pan layer which occurred 85 to 105 cm depths. This layer which is rich in $CaCO_3$ can react and adsorb NO_3-N (Jurinak and Griffin, 1972).

Summary on mineral N availability

The application of NH_4NO_3, $(NH_4)_2SO_4$, and SCU at the practical rate of 56 kg N/ha to winter wheat at the Blue Creek Experimental Station affected the available mineral N mostly in the 0-30 cm soil layer in the fall. Ammonium nitrate gave the highest amounts of the mineral N, followed by $(NH_4)_2SO_4$. S-coated urea yielded the lowest. The larger amounts of mineral N was in the nitrate form. However, the mineral N contents in this layer decreased to those of the unfertilized plots by April and May of the following year.

No significant difference in the NH_4-N or NO_3-N contents in the 30-75 cm or 75-120 cm soil depths among various N treated plots was observed on any sampling date in the fall or spring. The mineral N contents of the N treated

plots were similar to that of the unfertilized plots, regardless of the sampling dates in the fall and spring.

From the results of Experiment I, it is concluded that the application of NH_4NO_3, $(NH_4)_2SO_4$ and SCU at the practical rate of 56 kg N/ha to winter wheat at the Blue Creek Experimental Station affected the mineral N mostly in the 0-30 cm soil layer in the fall. Although the N fertilizers did increase the amounts of mineral N compared to the unfertilized plot, there was no significant difference in grain yield over the unfertilized plot. Ammonium nitrate gave the highest amounts of mineral N, followed by $(NH_4)_2SO_4$. S-coated urea yielded the lowest. However, grain yields tended to be slightly higher in the fertilized plots which was due to higher available N in the 0-30 cm soil depth in the fall.

Nitrogen fertilization increased the percentages of grain protein and N content in the grain significantly, but grain from all fertilized plots had similar percentages. Fried (1975) also found no difference in N content in grain among NH_4NO_3, $(NH_4)_2SO_4$, and urea.

Experiment II. Nitrate Movement in Soil Planted to Winter Wheat After the Application of Ammonium Nitrate

Environmental conditions before the November and May soil samplings

Soil moisture and temperature influence the rate and extent of N transformations in soil. These factors occurring following N application must be reflected in the mineral N contents at the first sampling date (November 5, 1974) and the last sampling date (May 28, 1975).

The soil moisture contents at the fertilizer application time (October 10, 1974) at the depths of 0-15, 15-30, 30-45, and 45-120 cm were 11, 16, 18, and 19 percent, respectively, but the soil surface was dry.

The initial rainfall of 2.36 cm occurred during October 21 to 24, 1974. The highest amounts of rainfall--3.18 cm--occurred on October 31, 5 days prior to the first soil sampling. The total rainfall falling between the dates of N application and the November soil sampling was 6.48 cm. The maximum and minimum soil temperatures at a 2.5 cm depth during this same period ranged from 6 to 20 and -1 to 5 C, respectively.

The precipitation from the November sampling date to the May sampling date in 1974-1975 was 22.45 cm. A nearly constant snow cover existed from December 1974 to March 1975. In April and May, some spring rains fell. The soil surface was saturated with moisture in late April and was still moist in May. The maximum and minimum soil temperatures in May were 7 to 34 and -6 to 9 C, respectively.

Levels of mineral N in unfertilized plots

At the time of N application (October 10, 1974), the 0-15 cm layer of soil had 33 kg/ha of NO_3-N, and only 7 kg/ha in the 15-30 cm layer. Ammonium N was a low value of 4 kg/ha in each of the two layers. In the deeper layers down to 120 cm the amounts of both forms of N ranged from 2 to 11 kg/ha.

The amounts of NH_4-N and NO_3-N in the soil profile to 120 cm depth sampled on November 5, 1974 are shown in Figure 10 or in Table 24 and Table 25

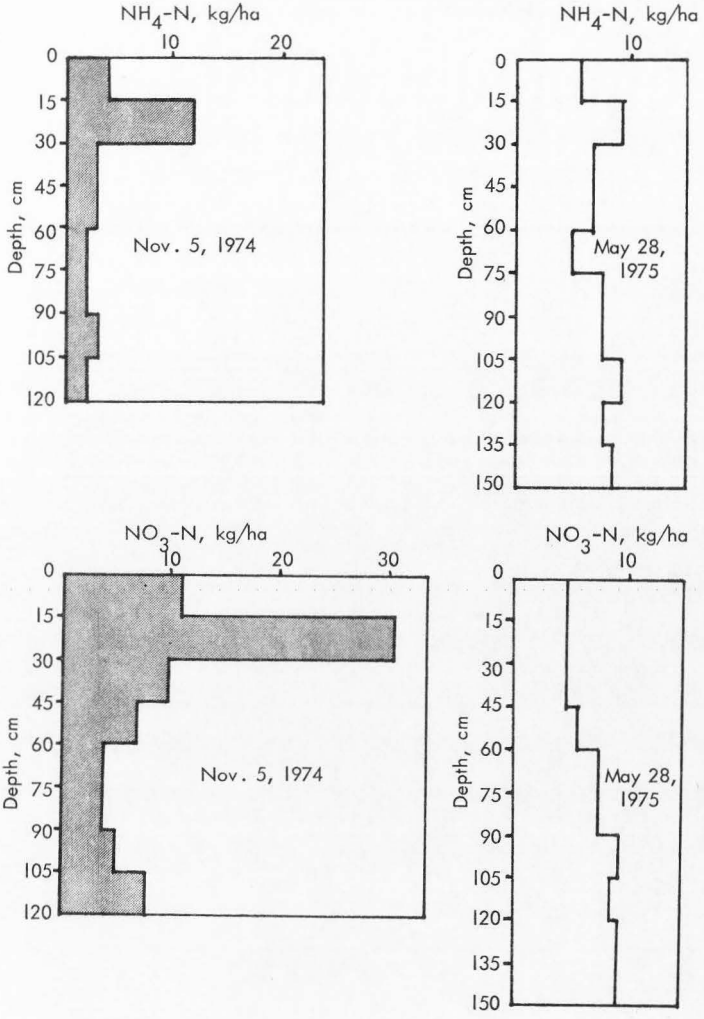


Figure 10. NH_4-N and NO_3-N contents in the soil profile on November 5, 1974 and May 28, 1975, for the unfertilized plots planted to winter wheat.

for NH_4-N and NO_3-N, respectively. On November 5 the highest amounts of mineral N, 31 and 12 kg N/ha for NO_3-N and NH_4-N, respectively, were found in the 15-30 cm soil depth. The changes in distribution in NH_4-N and NO_3-N contents at the November 5 sampling are probably due to mineralization of soil N in the moistened soil and partly due to the movement downward from the soil surface in the 6.48 cm of rain water. Below the 30 cm depth, NH_4-N and NO_3-N contents in the profile were not changed. The mineral N in the 120 cm profile (111 kg N/ha) was predominately present in nitrate form (80 kg N/ha).

The levels of NH_4-N and NO_3-N in the soil on the May 28, 1975 sampling had similar patterns. Both forms of N decreased in the upper soil layers. The mineral N values for the 120 cm profile were 61 and 56 kg N/ha for NH_4-N and NO_3-N, respectively.

Movement of NO_3-N in the soil profile

The magnitudes of N movement, especially NO_3-N, through the soil profile can be estimated through a combination of: (1) the changes in mineral N, mostly NO_3-N, contents at the beginning (November 5, 1974) and at the last soil samplings (May 28, 1975); (2) the changes in the slightly reactive Br^- distribution in the soil profile with time; and (3) the amount and distribution changes in the total N contents in the soil profile. Comparing the pattern of Br^- distribution in the soil profile should indicate the maximum potential for NO_3-N movement or leaching loss from the upper soil profile.

The largest NH_4-N contents in the soil profile on November 5 and May 28 (see Figure 11 or Table 26) occurred in the 0-15 cm layer (294 and 48 kg N/ha, respectively). Small increases of NH_4^+ occurred in the 30-45 cm depth between fertilization on October 10 and sampling on November 5. The NH_4^+ contents at the deeper layers were similar on both sampling dates. By May 28 most of the NH_4-N had been nitrified and immobilized.

By November 5, NO_3-N contents of 100, 167, and 17 kg N/ha were found in the 0-15, 15-30, and 30-45 cm layer, respectively (see Figure 12 or Table 27). These values, 26 days after fertilization (but the soil surface received rainfall first time on October 21), accounted for about 270 kg N/ha. This added to NH_4^+ values totals about 135 percent of the added N rate, or 35 percent more than was added. These indicated that some N had moved down to the 45 cm soil depth since the time of N fertilization as a result of the 6.48 cm of rainfall in late October 1974. The soil moisture in the profile also showed that water had moved down as far as 45 cm depth (Figure 13). Below this depth the moisture contents at the N application time and at November sampling time were unchanged down to 120 cm.

Figure 12 also shows the NO_3-N distribution on November 5, 1974 and May 28, 1975. In November most of the NO_3-N still existed in the 0-30 cm layer but by May (6 months later) most of it had moved down deeper, even to the 150 cm depth. The highest concentrations were found in the 45 to 90 cm depth. Under the conditions of the study area and the conventional rate of N applied (56 kg N/ha), much less NO_3-N would have moved down to the deeper layer.

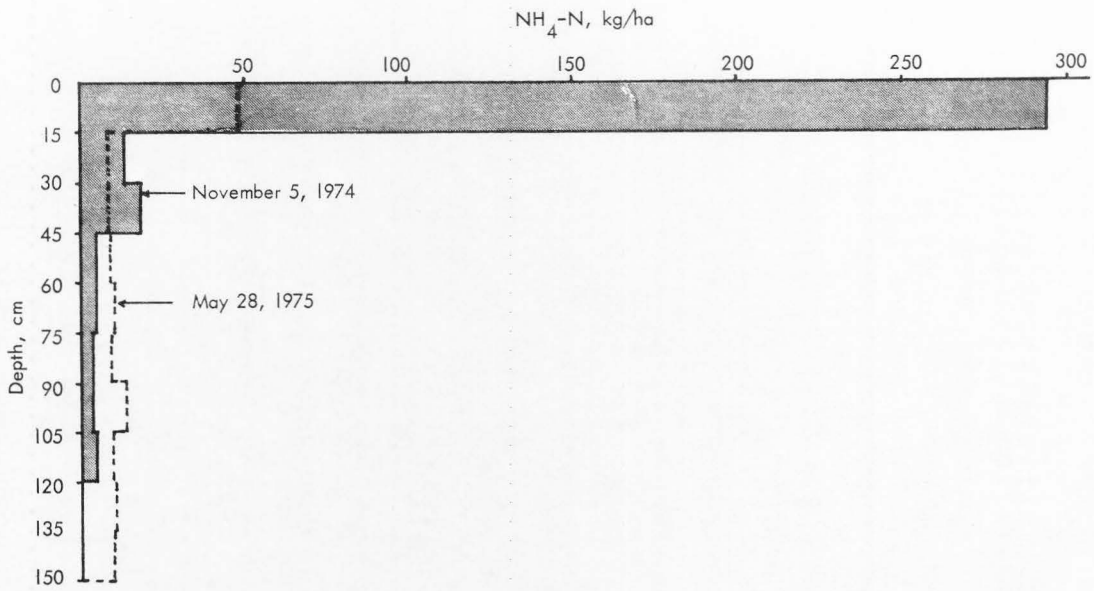


Figure 11. NH_4-N distribution in the soil profiles on November 5, 1974 and May 28, 1975. Nitrogen application was 400 kg N/ha with NH_4NO_3 broadcast after winter wheat was seeded.

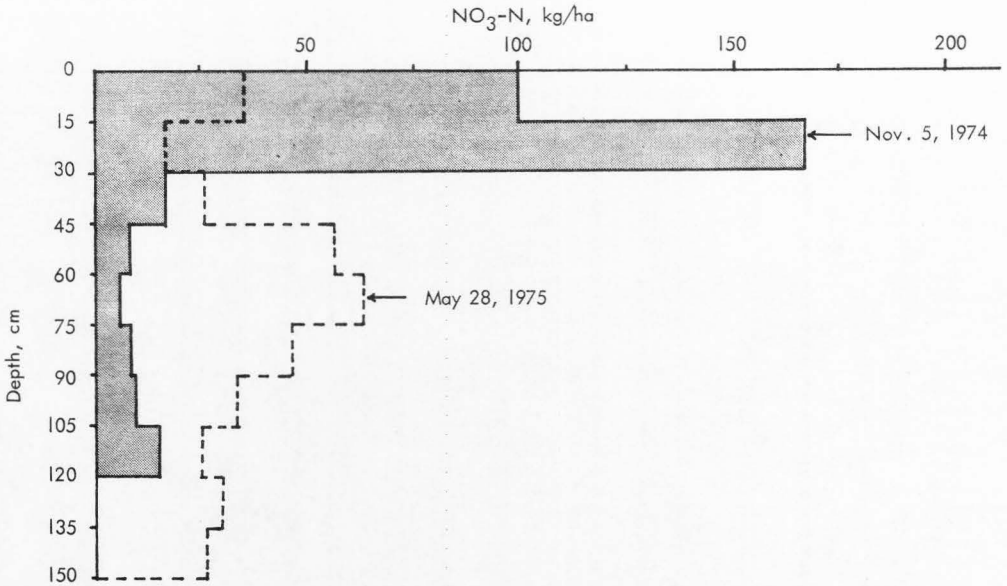


Figure 12. NO_3-N contents in the soil profile on November 5, 1974 and May 28, 1975. There was 400 kg N/ha with NH_4NO_3 broadcast after winter wheat was seeded.

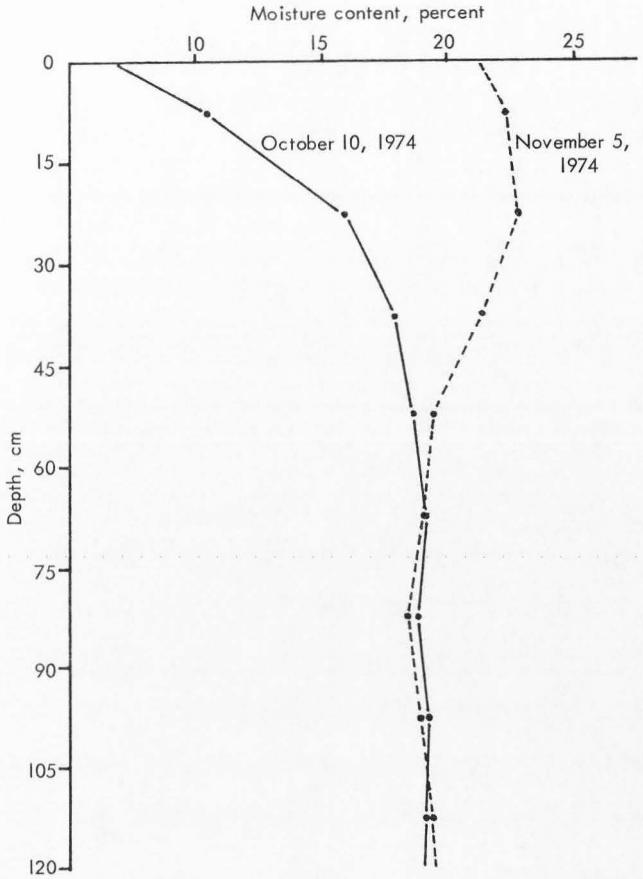


Figure 13. Soil moisture contents in the profile on two soil sampling dates.

Much of it would be used or immobilized by micro-organisms. But with the high rate of N used in this study (400 kg N/ha), there is a large pool of NO_3-N present in the soil. Snow melting slowly in April and early May produced a considerable amount of water capable of moving considerable NO_3-N below the 150 cm soil depth.

The difference in the mineral N (NH_4-N and NO_3-N) contents in the 0-120 cm soil profile of the fertilized plots on November 5 and May 28 was 34.8 percent of the added N. This decrease over the winter can be a result of several possibilities including immobilization in the soil, volatilization as gaseous N and/or leaching below the 120 cm sampled depth, as indicated by the higher NO_3-N in the 120-150 cm layer sampled in May, 1975.

Bromide (Br^-) tracer techniques

Another approach in estimating the movement of soluble ions (NO_3^-) in the profile is to follow the distribution of relatively unreactive Br^- in the soil profile.

Figure 14 or Table 28 shows the bromide distribution through the 0-120 cm soil profile in the control plots having no added bromide on November 5, 1974 and May 28, 1975. It shows that on November 5 the amounts of apparent bromide in the profile were low (2 to 6 kg/ha in each 15 cm layer). This small base-line value for bromide is much lower than values where bromide was added as a tracer.

Bromide distribution in the soil profile of treated plots is shown in Figure 15 or Table 29. The increase in bromide content in the bromide-treated plots on

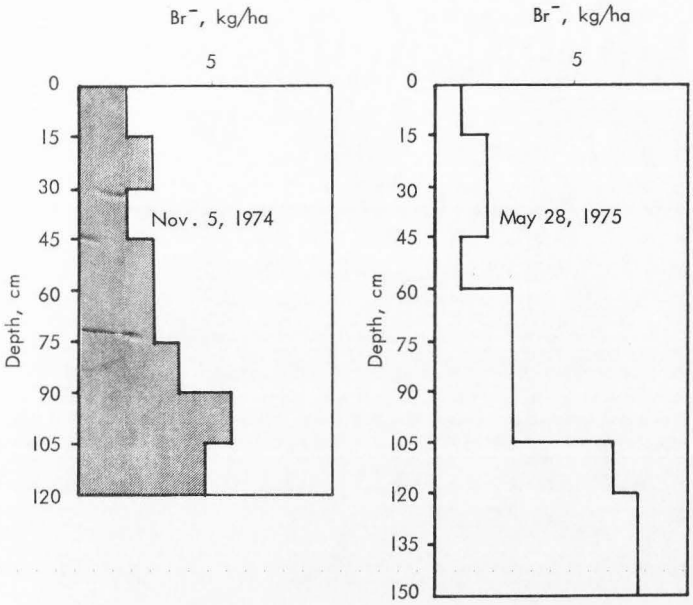


Figure 14. Bromide content in the soil profile on two soil sampling dates in control plots planted to winter wheat.

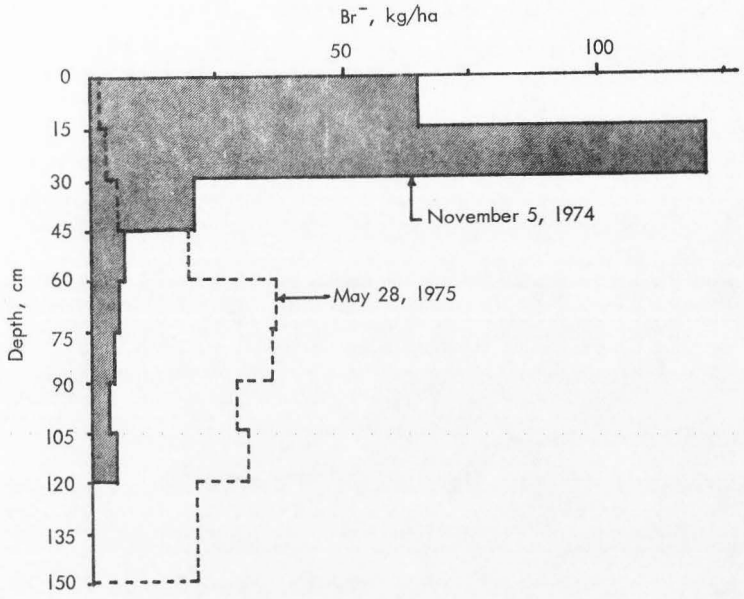


Figure 15. Bromide contents in the soil profile on the two soil sampling dates. Soil received 200 kg Br^-/ha as KBr broadcast on the surface after winter wheat was seeded on October 5, 1974.

the November 5 sampling was 205 kg/ha, which calculated to be close to the 200 kg/ha of bromide added. Because N and bromide materials were added by the same method, apparent differences in the N measured and the N added are not believed to be uneven addition. Figure 15 shows that the highest Br^- content (122 kg/ha) was found in the 15-20 cm layer. The bromide distribution also indicated that some had moved down to as deep as 45 cm; this distance was similar to the depth of NO_3-N movement as shown in Figure 12. Below 45 cm the Br^- content was similar to that of the control plot. On May 28, the Br^- had been washed down to the 150 cm depth with the highest concentration occurring between 60 and 120 cm compared to a NO_3-N maximum in the 45 to 90 cm depth (Figure 12). All of the added Br^- appeared to move deeper than 45 cm. The bromide contents in the soil profile are shown in Table 6.

The amount of Br^- leached below 120 cm by May 28, 1975 was calculated to be about 71 kg/ha which was equivalent to about 35.5 percent of the Br^- added. This value was close to the mineral N deficit of the fertilized plot. It was assumed that little Br^- was absorbed by wheat plants because it is not an essential nutrient element for crops. However, it is possible that some uptake occurred.

Comparing the NO_3-N and Br^- content distribution in the profile, it is evident that their patterns were similar in both November and May samplings. Both NO_3-N and Br^- moved downward in similar amounts and rates to the 150 cm depth.

Table 6. Average bromide contents (kg/ha) in the soil profile sampled on November 5, 1974 and May 28, 1975.

Depth (cm)	November 5, 1974		May 28, 1975	
	Control	200 kg Br^-/ha	Control	200 kg Br^-/ha
0-15	2	65	1	2
15-30	3	122	2	3
30-45	2	21	2	6
45-60	3	7	1	19
60-75	3	6	3	37
75-90	4	4	3	36
90-105	6	3	3	28
105-120	5	5	7	31
120-135			8	21
135-150			8	21
Total (0-120 cm)	28	233	22	162

In the experimental year a near maximum snow period existed resulting in a nearly maximum downward movement of NO_3-N at this Blue Creek Experimental Station soil.

Total soil N contents

Another approach to estimate the downward movement of N from this study was to compare the total soil N at the November and May soil samplings. In the

unfertilized plot the difference in total N in November 1974 and May 1975 was negligibly small. But the difference on the two dates in the fertilized plot was 280 kg N/ha, excluding 122 kg N/ha uptake by plant, which is equivalent to about 40 percent of the added N (Table 7). The loss of 40 percent in fertilized plots is assumed to be lost by gaseous N and leaching below 120 cm depth. The N loss estimated by the difference in total N in the profile was slightly higher than that estimated from the mineral N. However, unaccounted-for-N was similar as determined by the two approaches. It is noted that the total N in the soil profile of the unfertilized plots or fertilized plots varied, which may be due to the location of the plots used.

Effects of a heavy rate of N fertilizer on dryland winter wheat yields

Table 8 shows the experimental data of dryland winter wheat receiving the 400 kg N/ha of broadcast NH_4NO_3 in plots at the Blue Creek Experimental Station in the October 1974 to August 1975 growing season.

It is obvious that the wheat yield components between unfertilized plot and fertilized plot were significantly different except for the grain yields. Similar grain yields but higher straw yields from the fertilized plots were attributed to the lush vegetative growth where high N rates were applied.

The fertilized plot gave straw yields twice as high as the unfertilized plot. Similar values were found for the straw N contents and in total N uptake in grain. Nitrogen uptake in straw from plots with 400 kg N/ha was about 5 times greater uptake from unfertilized plots. The grain protein of fertilized plots increased

Table 7. Total N in kg/ha of soil at the Blue Creek Experimental Station for soil receiving 400 kg N/ha and planted to dryland winter wheat in 1974-1975 growing season.

Depth (cm)	Unfertilized Plot Plot No. I	III	V	VI	Average	Fertilized Plot Plot No. II	IV	VII	VIII	Average
					November 5, 1974					
0-60	7,850	8,390	7,580	6,710	7,630	8,410	9,320	6,800	8,510	8,260
60-120	-	5,470	5,230	-	5,350	5,160	5,700	-	-	5,430
0-120	-	13,860	12,810	-	12,980	13,570	15,020	-	-	13,690
					May 28, 1975					
0-60	8,170	8,470	7,130	7,160	7,730	7,840	8,890	6,560	8,150	7,860
60-120	5,200	5,280	5,120	5,470	5,270	5,170	5,850	5,100	6,070	5,550
0-120	13,370	13,750	12,250	12,630	13,000	13,010	14,740	11,660	14,220	13,410

Table 8. Effects of heavy N fertilization on dryland winter wheat yields at the Blue Creek Experimental Station. Wheat was grown from October 1974 to August 1975.

Wheat Yield Components	Wheat Yields†	
	Unfertilized	400 kg N/ha
Grain yield, kg/ha	1809 a	2349 a
Straw yield, kg/ha	2903 a	6871 b
Grain protein content, %	13.2 a	19.6 b
Straw N content, %	0.3 a	0.6 b
Total N uptake in grain, kg N/ha	41.8 a	80.4 b
Total N uptake in straw, kg N/ha	8.9 a	41.9 b

†Means are the averages of 4 observations. Data followed by the different letters are significantly different at the 0.05 level.

nearly half to 19.6 percent. However, even the unfertilized plot had a realtively high grain protein content; this might be the result of rather fertile soil plots at this station.

Summary

Data from this study at the Blue Creek Experimental Station indicate the potential exists on wet years for considerable amounts of NO_3-N to move below the 120 cm layer. Evidence of NO_3-N moved down to at least 150 cm depth was also observed. The exceptionally heavy rate of N applied did not increase

grain yield, but did increase straw yield, grain protein content, straw N content, and total N uptake in grain and in straw significantly.

Experiment III. NH_3-N Volatilization from Soil Receiving N Fertilizers

It has been known that several environmental conditions affect the NH_3-N loss from the soil supplied with N fertilizer. Soil properties and climatic factors are considered as the most important ones as well as soil-plant cropping management or conventional cultural practices at the present time. This part of the research emphasizes some soils and climatic factors on N loss as NH_3 from the N-fertilized soil. Particularly, an attempt was made to study the factors which prevail in practical (economical) crop production. Most of the work has been conducted in the laboratory, but parts of it were done in the field.

Laboratory experiments

Effects of different sizes of pellet urea on NH_3-N loss from noncalcareous soil. Different sizes of pellet urea used in this study were: (1) 2.00-2.50 cm diameter (about 150 pellets/g), (2) 1.34-2.00 mm (600 pellets/g), (3) 0.59-1.34 mm (3,300 pellets/g), and (4) pulverized-pellet urea. Urea at a rate of 100 kg N/ha was applied to the wet Timpanogos silt loam soil which is a non-calcareous soil. The amounts of NH_3-N evolved and water losses were simultaneously measured daily up to 14 days after the N application.

There was no difference 14 days after application in the rates of NH_3-N loss from the soil receiving the different sizes of urea pellets. The rates of

water loss from the treated soil were also of the same magnitude for all treatments. The amounts of accumulated NH_3-N losses from the soil ranged from 9.4 to 10.6 percent of the applied N. The amounts of total water losses among the treatments were similar with about 122 ml lost in 14 days (Figure 16).

The average rates of NH_3-N and water losses from soil to which various sizes of urea pellets were added are shown in Figure 17. It is obvious that the patterns of the rate of NH_3-N loss and the rate of water loss were different. The rate of NH_3-N loss increased as the time from the urea application increased up to 7 days. Thereafter the rate of NH_3-N loss decreased rapidly. On the other hand, the rate of water loss seemed to be almost constant until the tenth day. Similar results have been found by Chao and Kroontje (1964) who concluded that the NH_3-N loss and water evaporation from the fertilized soils follow different patterns of loss.

The lack of any difference of accumulative NH_3-N loss as affected by pellet size is probably the result of high solubility of urea in water. Urea dissolved on the soil surface rather rapidly after application regardless of the pellet size used. Even the larger urea pellets disappeared within 2 hours. No volatilized NH_3-N was observed from any treated soil until 10 hours after fertilization.

Similar results have been reported by Gasser (1964). He noted, however, that the forms of urea (pelleted, crystalline, and solution) applied did cause differences in NH_3-N losses from different soils but not within soil. Similarly, Watkins, et al. (1972) found that there was no significant relationship between

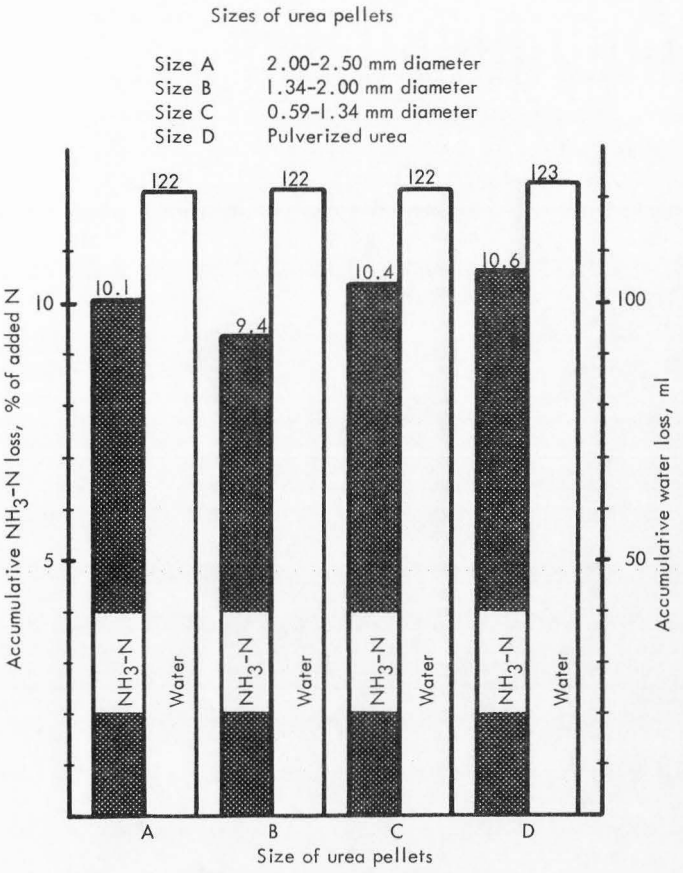


Figure 16. Accumulative losses of NH_3-N from Timpanogos soil at room temperature as influenced by different sizes of urea pellets applied to the soil surface at a rate of 100 kg N/ha, and its relationship to the amounts of water losses.

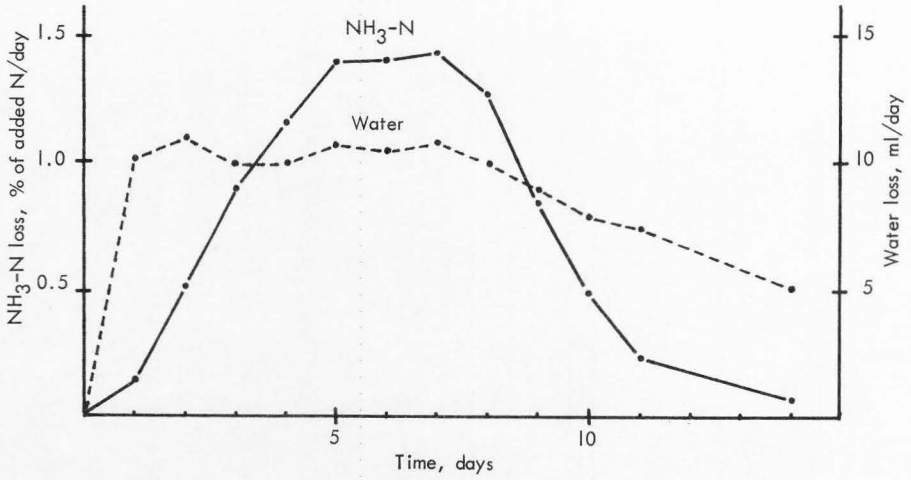


Figure 17. Comparison of the average rate of NH_3-N and rate of water loss at room temperature from Timpanogos soil receiving 100 kg N/ha with urea applied to the wet soil surface.

the NH_3-N losses and urea pellet sizes ranging from 0.5 cm in diameter (large pellet) to crystals about 1 mm in diameter. Nomik (1973) reported that the total NH_3-N losses were 20 percent and 22 percent from the forest soil receiving tableted urea (2.06 g/pellet) and small pellets of urea (280 pellets/g), respectively, but there was some slight difference in the rates of NH_3-N loss during the 28 day period.

Therefore, it is assumed that the sizes of urea used in this study did not influence the NH_3-N losses from the noncalcareous Timpanogos soil used. The urea of mixed pellet sizes supplied from the fertilizer company is suitable for use in the studies of NH_3-N losses. Although $(NH_4)_2SO_4$ and NH_4NO_3 materials were not similarly tested, each has almost similar sizes, both are very soluble and would be expected to react similarly to the urea.

Effects of N sources on NH_3-N volatilization from noncalcareous soil. Nitrogen sources, consisting of $(NH_4)_2SO_4$, NH_4NO_3, and urea, were applied to the surface of the wet Timpanogos soil at a rate of 200 kg NH_4-N/ha. The amounts of NH_3-N losses in the laboratory at room temperature were measured daily for 14 days.

Figure 18 shows the accumulative losses of NH_3-N evolved from the soil having $(NH_4)_2SO_4$, NH_4NO_3, or urea added. It is evident that considerable NH_3-N loss occurred from the soil receiving urea. The amounts of NH_3-N losses in 14 days from soil treated with $(NH_4)_2SO_4$, NH_4NO_3, and urea were 1.0, 0.5, and 13.7 percent of added N, respectively.

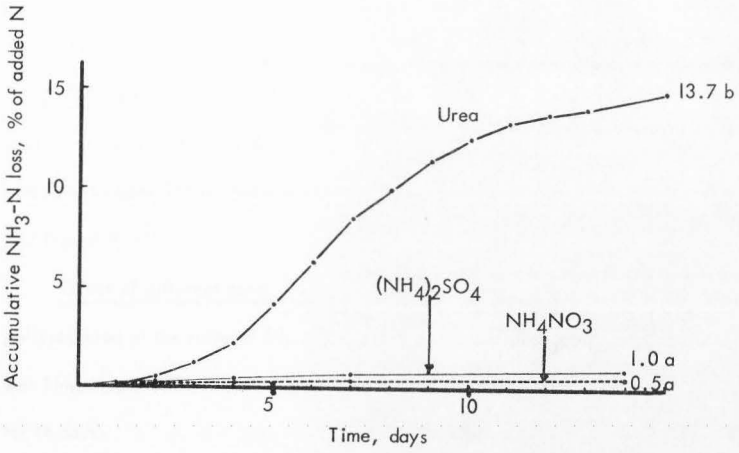


Figure 18. Accumulative NH_3-N losses from noncalcareous Timpanogos soil at room temperature as influenced by N sources applied to the soil surface at a rate of 200 kg NH_4-N/ha.
Data at the end of each curve are total NH_3-N losses.
Different letters indicate losses that are statistically different at the 0.05 level.

The higher NH_3-N loss from the urea-treated soil is probably caused by the higher soil pH caused by the hydrolysis of urea. Urea fertilization increases the pH of a soil surface more than does $(NH_4)_2SO_4$ or NH_4NO_3. Whitehouse and Leslie (1973) reported that the pH of the soil receiving urea increased more than did $(NH_4)_2SO_4$; $(NH_4)_2SO_4$ caused a greater increase in soil pH than did NH_4NO_3 (Fenn and Kissel, 1973). A higher soil pH resulting from urea application but no effect on soil pH by added $(NH_4)_2SO_4$ was also reported by Acquaye and Cunningham (1965), Harding et al. (1963), Kresge and Satchell (1960), and Prasad (1976).

Effect of different rates of urea on NH_3-N loss from noncalcareous soil. The pelleted urea at the rates of 50, 100, 200, and 400 kg N/ha were applied to the wet Timpanogos soil surface. The amounts of NH_3-N losses were measured daily for 14 days.

Figure 19 shows the accumulative NH_3-N losses from soil receiving different rates of urea. Increasing the rates of urea-N applied from 100 to 400 kg N/ha significantly increased the percentage of NH_3-N lost. The rates of 50 and 100 kg N/ha caused no significant difference in NH_3-N loss. The NH_3-N losses from soil supplied with 50, 100, 200 and 400 kg N/ha were 11.0, 12.7, 17.7, and 21.6 percent of the applied N; these percentages are equivalent to 5.5, 12.7, 35.4, and 86.4 kg N/ha, respectively. Similar results using urea have been reported by Acquaye and Canningham (1965), Kresge and Satchell (1960), Overrein and Moe (1967), and Shankaracharya and Mehta (1971).

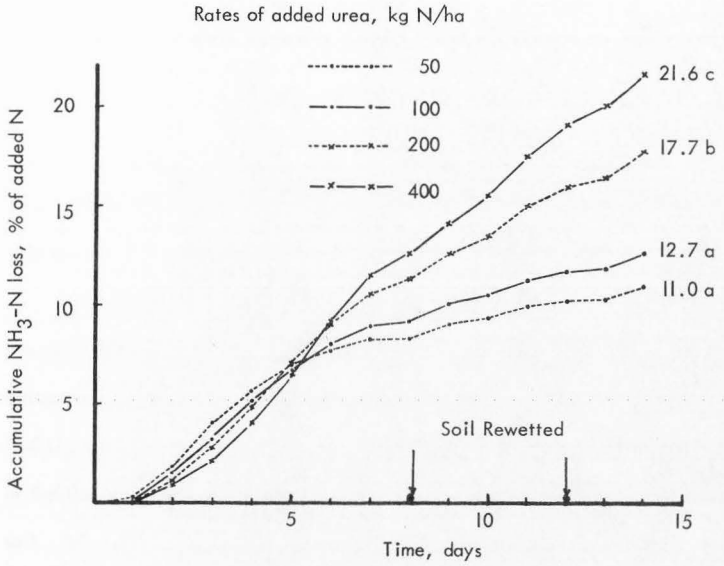


Figure 19. Accumulative NH_3-N losses from Timpanogos soil at room temperature as influenced by adding urea to the soil surface at different rates. Data at the end of each curve are the total NH_3-N losses. Different letters indicate significantly different losses.

The higher amounts of NH_3-N lost from soil at rates of 200 and 400 kg N/ha were attributed to the following factors: (1) the urea hydrolysis reaction behaves as a first-order reaction with respect to urea concentration (Ardakana et al., 1975; Overrein and Moe, 1967), so the pH of the soil is increased by the larger amounts of urea as reported by Kresge and Satchell (1960), and Overrein and Moe (1967); and (2) the extent or percentage of NH_4^+ increases. It is known that the sorptive capacity of the soil for NH_4^+ is finite. Therefore, increasing the concentration of NH_4^+ will decrease the proportion of NH_4^+ being sorbed allowing the NH_3-N losses to be higher from soil receiving larger amounts of urea-N.

Effects of the carbonates in the soil on NH_3-N volatilization. The kinds of the carbonate materials used for this study were $CaCO_3$, $BaCO_3$, and highly calcareous soil (Millville silt loam, pH 7.8) which contains about 28 percent of $CaCO_3$ equivalent, part of which is $MgCO_3$. Five percent by weight of $CaCO_3$ or $BaCO_3$ was added and mixed thoroughly with the noncalcareous Timpanogos soil. After the water was added, the samples were equilibrated for 2 days before the different N sources were applied at a rate of 200 kg NH_4-N/ha to the wet soil surface. The amounts of NH_3-N losses were measured daily for 14 days.

The accumulative NH_3-N losses in 14 days from the noncalcareous Timpanogos soil receiving 5 percent $CaCO_3$, $BaCO_3$, and from the calcareous Millville soil are illustrated in Figures 20, 21, and 22, respectively. The total NH_3-N loss was significantly higher from the soils fertilized with $(NH_4)_2SO_4$ than from soils fertilized with NH_4NO_3 or urea for each kind of carbonate treatment.

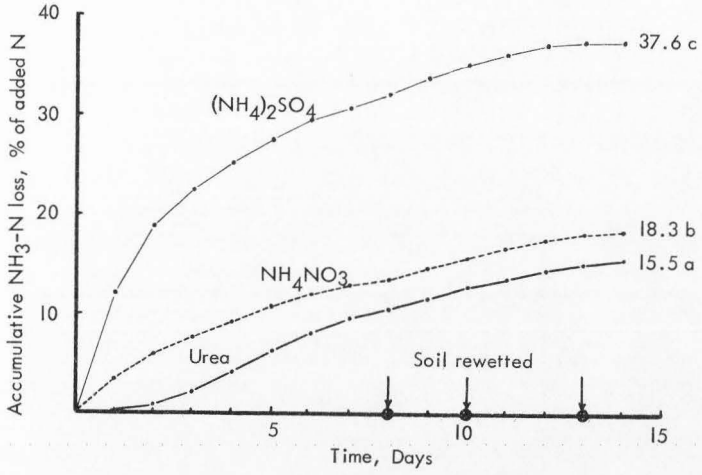


Figure 20. Accumulative NH_3-N losses from Timpanogos soil at room temperature as influenced by the addition of 5 percent by weight of $CaCO_3$ and by various N sources applied to the soil surface at a rate of 200 kg NH_4-N/ha.
Data at the end of each curve are the total NH_3-N losses.
Different letters indicate statistically significant differences in NH_3-N losses.

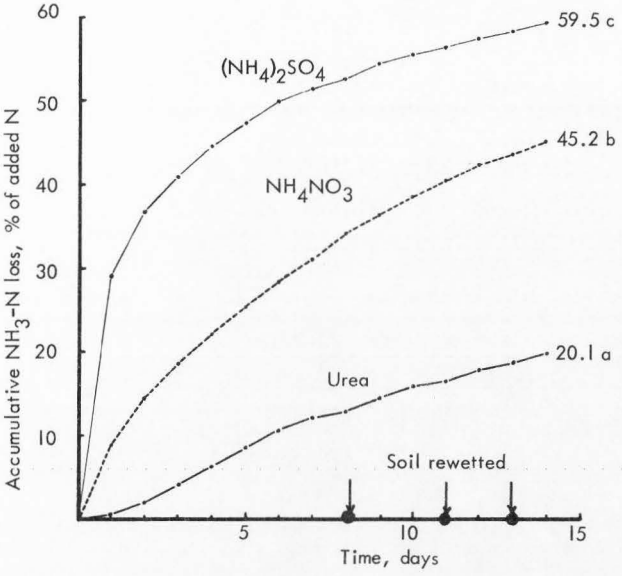


Figure 21. Accumulative NH_3-N losses from Timpanogos soil at room temperature as influenced by the addition of 5 percent by weight of $BaCO_3$ and by various N sources applied to the soil surface at a rate of 200 kg NH_4-N/ha.
Data at the end of each curve are the total NH_3-N losses.
Different letters indicate significantly different losses.

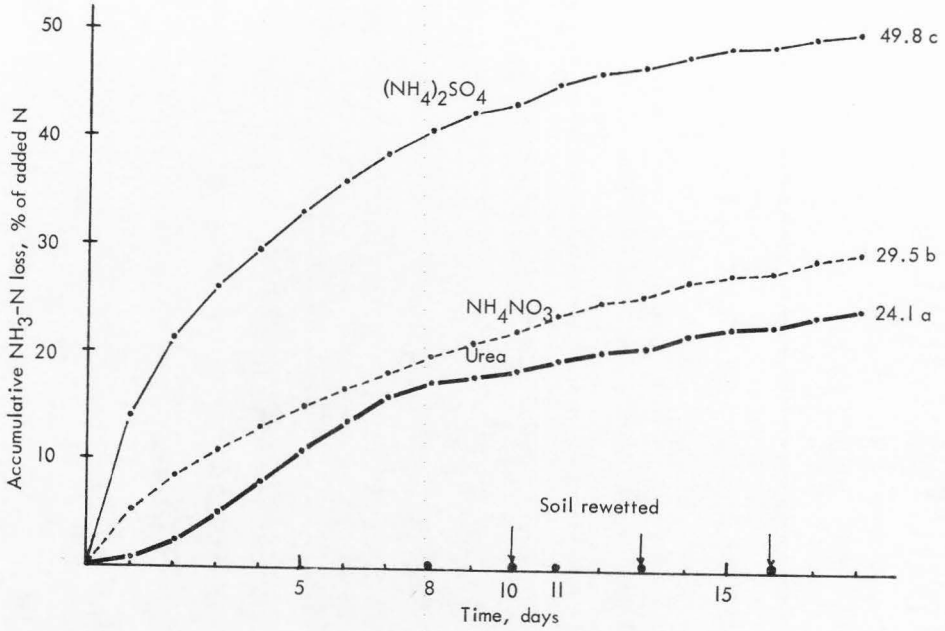


Figure 22. Accumulative NH_3-N losses from highly calcareous Millville soil at room temperature as influenced by N sources applied to the soil surface at a rate of 200 kg NH_4-N/ha.
Different letters indicate statistically significant differences in the losses.

The patterns of NH_3-N losses from the soil receiving 5 percent $CaCO_3$ were different for the three fertilizer materials. The rates of NH_3-N losses from $(NH_4)_2SO_4$ and NH_4NO_3 were highest during the first day and decreased with time. Ammonia-N losses from soil with $(NH_4)_2SO_4$ after the first, second, and third days were 12.1, 6.5, and 3.8 percent of added N, respectively. Corresponding values for NH_4NO_3 were 3.7, 2.2, and 1.8 percent of added N. However, the highest NH_3-N losses from urea-treated soil were in the fourth, fifth, and sixth days.

The higher loss of NH_3-N from $(NH_4)_2SO_4$ may be chiefly due to the insolubility of reaction products formed with $CaCO_3$ and $(NH_4)_2SO_4$ resulting in formation of the unstable $(NH_4)_2CO_3$ as proposed by Fenn and Kissel (1973). Ammonium nitrate would not form much unstable $(NH_4)_2CO_3$ which is largely independent of $CaCO_3$. Part of the urea applied might also migrate downward into the soil more than the charged NH_4^+ from $(NH_4)_2SO_4$ and NH_4NO_3. Therefore, the amount of NH_3-N lost from urea-treated soil was not influenced by $CaCO_3$ addition.

The patterns of NH_3-N losses from soil receiving 5 percent by weight of $BaCO_3$ (Figure 21) were similar to losses from soil with $CaCO_3$ (Figure 20), but the total amounts and the rates of NH_3-N losses were higher when $BaCO_3$ was added. For example, the rates of NH_3-N losses from $(NH_4)_2SO_4$ in the first, second, and third day were 29.3, 7.5, and 4.5 percent of added N, respectively. Corresponding figures for NH_3NO_3 were 9.2, 5.3, and 4.2 percent. The more than doubled loss of NH_3-N caused by $BaCO_3$ compared to

that caused by $CaCO_3$ was attributed to the very insoluble $BaSO_4$ formed from $(NH_4)_2SO_4$ and $BaCO_3$ which drives the reaction forming $(NH_4)_2CO_3$ more rapidly and completely.

The patterns of NH_3-N losses from N fertilizers applied to calcareous soil were similar to losses from the soil samples receiving 5 percent by weight of $CaCO_3$ or $BaCO_3$. The amounts of NH_3-N losses from calcareous soil during 14 days were 47.8, 26.7, and 21.8 percent of added N caused by the addition of $(NH_4)_2SO_4$, NH_4NO_3, and urea, respectively. The rates and accumulative losses of NH_3-N from calcareous soil or noncalcareous soil supplied with $CaCO_3$ are similar for the three N fertilizers tested (Figures 20 and 22).

Effects of the soil reaction (pH) on NH_3-N losses. The effects of two soil pH values were studied--pH 7.4 and pH 8.4. The desired pH values in the Timpanogos soil were obtained by the addition of $Ca(OH)_2$, followed by alternate wetting to field capacity and drying until the equilibrium pH wanted was reached. Ammonium sulfate, NH_4NO_3, or urea were then applied to the wet soil surface at the rate of 200 kg NH_4-N/ha. The NH_3-N evolved from the soil was measured daily for 14 days.

Figure 23 shows the accumulative NH_3-N losses during 14 days. The amount of NH_3-N loss was greatest at the higher soil pH (8.4) for all N fertilizers used. The higher pH increased NH_3-N loss from $(NH_4)_2SO_4$ or NH_4NO_3 more than it did the loss from urea. The higher pH caused the highest increase in NH_3-N loss (five fold increase or 24.4 percent) from $(NH_4)_2SO_4$ with lesser increases from NH_4NO_3 (four-fold increase or 16.6 percent) and urea (one-fourth increase

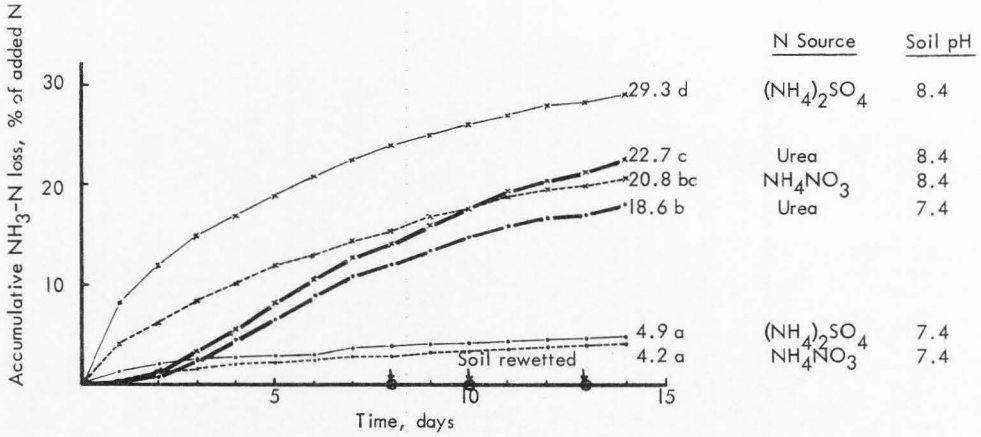


Figure 23. Accumulative NH_3-N losses from Timpanogos soil at room temperature as influenced by the soil pH and the N sources applied to the soil surface at a rate of 200 kg NH_4-N/ha.
Data at the end of each curve are the total losses.
Different letters indicate values statistically different from each other.

or 4.1 percent). The highest rate of NH_3-N loss was in the first day for both $(NH_4)_2SO_4$ and NH_4NO_3, but in the fifth day for urea.

The higher NH_3-N losses at pH 8.4 were thought to be the results of more NH_3 than NH_4^+ formation in the soil because the NH_3-NH_4^+ equilibrium is pH dependent. Higher pH's favor NH_3 formation. Also, small amounts of $CaCO_3$ might be formed after the application of $Ca(OH)_2$. No $CaCO_3$ could be detected in the soil of initial pH 8.4 by testing with 1 N HCl at the end of the experiment. However, the test is not very sensitive for $CaCO_3$ contents below several tenths of a percent.

Comparison of NH_3-N losses as influenced by added $CaCO_3$ and pH. $CaCO_3$, 10 percent by weight, was added to noncalcareous Timpanogos soil. Then the soil was wetted to field capacity. Other samples of the Timpanogos soil had the pH raised by adding NaOH solution to the sample and brought the soil moisture to field capacity by adding distilled water. Both sets of the soil samples were equilibrated for 2 days before the experiment was conducted. The pH values of the samples receiving 10 percent $CaCO_3$ and NaOH solution were 7.7 and 8.0, respectively. However, by the end of the experiment the soil pH values had fallen.

	10% $CaCO_3$	NaOH solution
When N fertilizer was added	pH 7.7	pH 8.0
At the end of experiment (10 days)	pH 7.3 - 7.6	pH 6.7 - 6.8

Ammonium sulfate and NH_4NO_3 were applied to the soil surface at the rate of 200 kg NH_4-N/ha. The NH_3-N evolved was measured every 3 hours for the first day, and daily thereafter up to 10 days.

The NH_3-N losses from the samples receiving 10 percent $CaCO_3$ were higher than losses from the samples to which NaOH was added to raise the pH to 8.0 (Figure 24). The NH_3-N lost was highest (36.7 percent) from $(NH_4)_2SO_4$ in samples having carbonate added. Even though the initial pH of the carbonate-treated samples was lower than the NaOH-treated samples, the NH_3-N loss was greater, nearly three-fold greater. The highest loss rates from all treatments occurred between the third and sixth hours after fertilization; then the rates decreased rather rapidly up to 24 hours. Thus, the highest NH_3-N losses occurred during the first day after N fertilizer application (Figure 25).

The gradual lowering of pH in the NaOH-treated soil makes a more detailed evaluation of the effect of pH versus effect of carbonate impossible.

Effects of temperature and rate of water loss on NH_3-N losses. Initial tests showed that higher temperatures increased NH_3-N losses. The NH_3-N losses during 21 days from Timpanogos soil receiving NH_4NO_3 at the rate of 56 kg N/ha at room temperature (22-24 C) was 0.5 percent of the added N but increased to 3.1 percent at 36 to 40 C. Higher temperatures also speed water losses.

Therefore, the first part of this study was set to study the relationships of NH_3-N losses to water losses at room temperature. Ammonium nitrate and urea at the rate of 100 kg N/ha were applied to Timpanogos soil. The rate of air flow

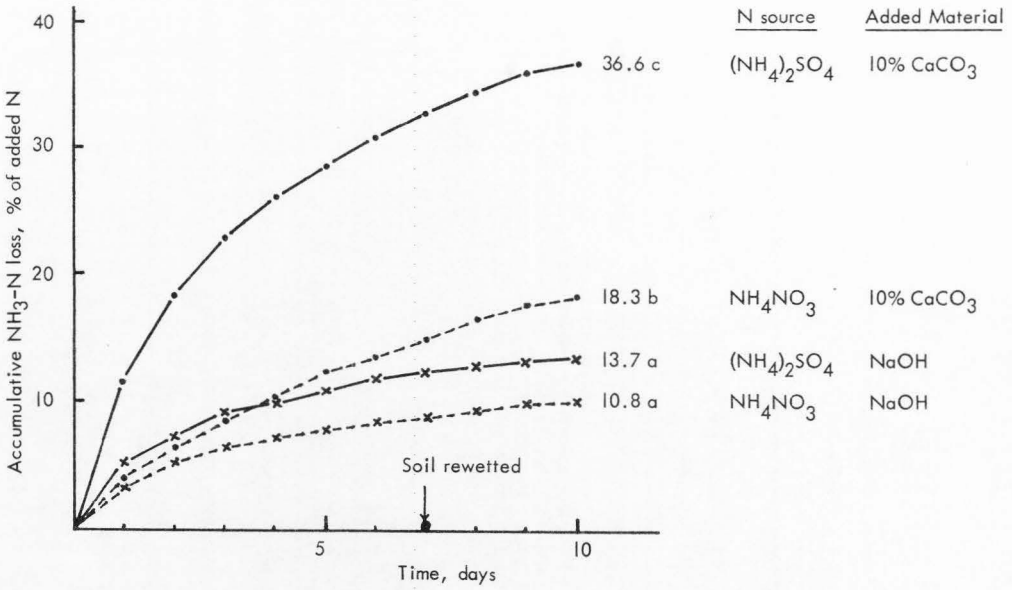


Figure 24. Accumulative NH_3-N losses from Timpanogos soil at room temperature as influenced by the addition of 10% by weight of $CaCO_3$ or NaOH solution and by various N sources applied at a rate of 200 kg NH_4-N/ha. Data at the end of each curve are the total NH_3-N losses.
Different letters indicate statistically different values for NH_3-N loss.

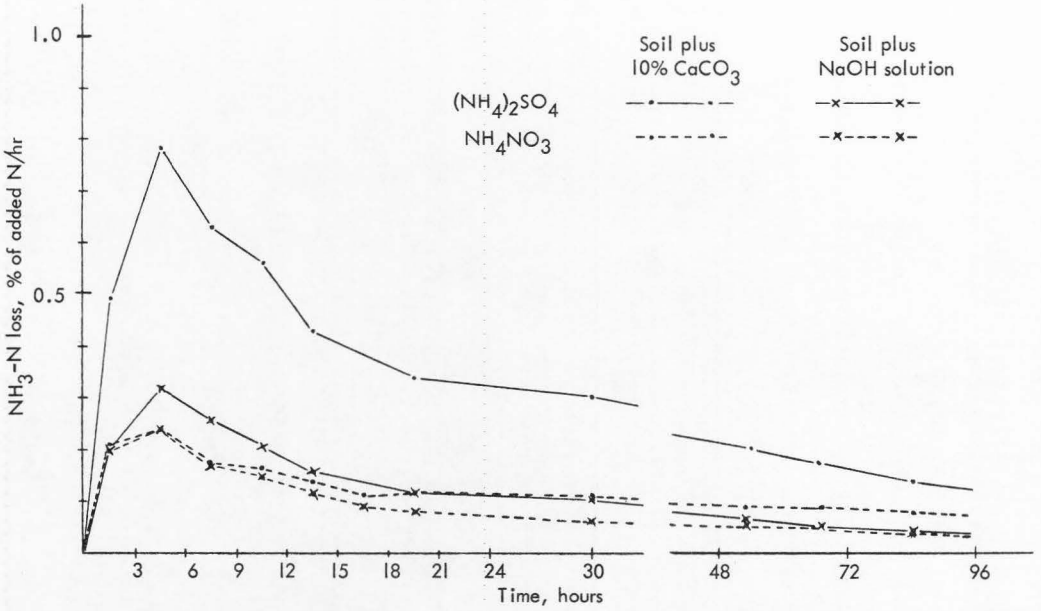


Figure 25. The rates of NH_3-N losses at room temperature from the Timpanogos soil receiving either 10% by weight of $CaCO_3$ or a NaOH solution which raised the pH values to 7.7 and 8.0, respectively. $(NH_4)_2SO_4$ or NH_4NO_3 were applied to the soil surface at a rate of 200 kg NH_4-N/ha.

used was about 800 cc/min. The losses of NH_3-N and water were measured at 12 to 24 hours intervals for 12 days.

The second part of the study was conducted to observe the effects of temperatures on NH_3-N and water losses. The temperature levels were room temperature, and temperatures ranging from 30 to 42 C. The first day when the soil surface was moist, the temperature was 30 C. But it increased to 42 C when the soil surface was dry. Two rates of air flow, 150 and 800 cc/min. were used. The higher temperatures were obtained with infra-red heat lamps and rubber coated, electric heating strips wrapped around the outside of the column near the soil surface. Urea at the rate of 100 kg N/ha was applied to the soil surface. As the water evaporated from the soil surface the temperature gradually increased with time. When the dried soil surface was rewetted, the soil temperature in the column decreased and began to gradually climb with drying. Therefore, the temperatures observed were ranges that existed during the experiment. No constant temperature could be maintained by the technique used. Further time to constantly adjust temperature did not seem warranted for the information.

The rates of NH_3-N and water losses from Timpanogos soil receiving NH_4NO_3 are shown in Figure 26, and from urea in Figure 27. The correlation between rates of NH_3-N and water losses from either NH_4NO_3 or urea was poor. For NH_4NO_3, the rate of NH_3-N loss was highest in the first day and then decreased rapidly, but the rates of water losses were relatively constant from the beginning until the end of the experiment. Similar results of a constant water loss were found from the samples with urea, but the rate of NH_3-N loss had a

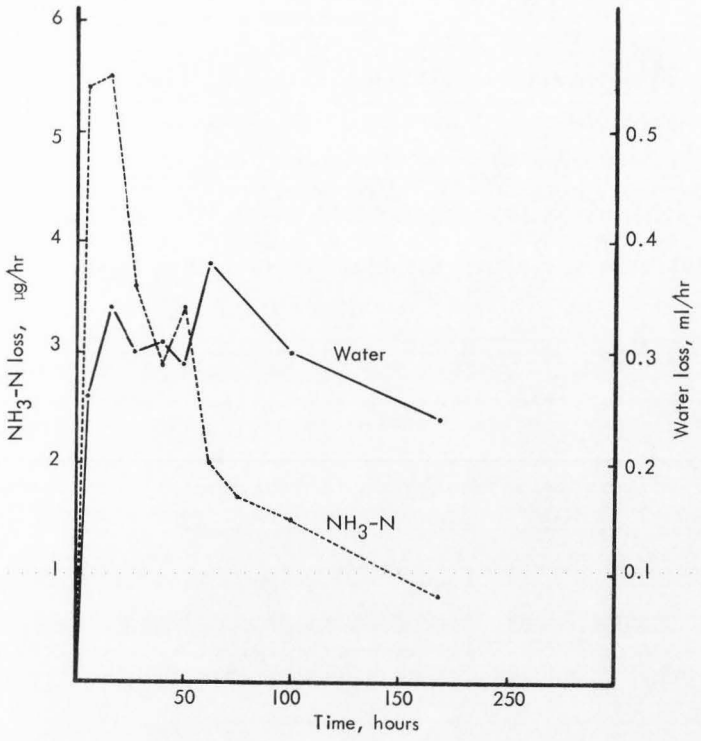


Figure 26. Comparison of the rates of NH_3-N and water loss from Timpanogos soil at room temperature. NH_4NO_3 was applied on the wet soil surface at a rate of 100 kg N/ha.

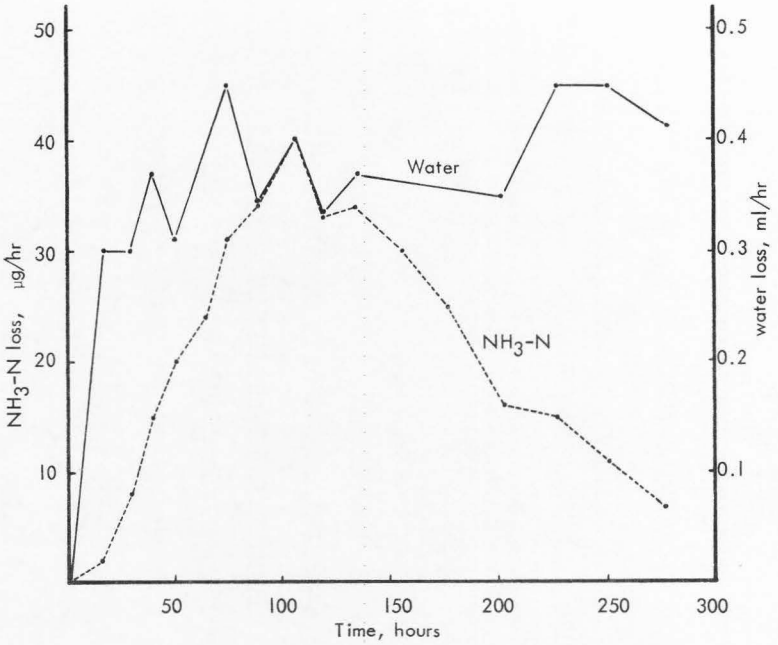


Figure 27. Comparison of the rates of NH_3-N and water loss from Timpanogos soil at room temperature. Urea was applied to the soil surface at a rate of 100 kg N/ha.

maximum during day 3 to day 6. After hour 200, an attempt was made to increase the amount of water losses from the urea treatments by increasing the air flow rate (Figure 27). The rates of NH_3-N loss still decreased in spite of the increases in water loss (from hour 200 to 250). Water loss and NH_3-N loss do not appear to be closely correlated.

Higher temperatures increased the rates of NH_3-N losses (Table 9). However, the time required to obtain the higher NH_3-N losses decreased as the soil moisture decreased. Rewetting the soil caused the rate of NH_3-N loss to increase slightly. Thus the total of NH_3-N losses was influenced by the temperature and the moisture in the soil. High temperatures along with low rates of air flow (less drying) gave the higher total NH_3-N losses (23.2 to 26.5 percent), but high temperatures with high air flow rates (rapid drying) tended to decrease total NH_3-N losses (11.7 to 16.9 percent) because soil soon dried.

There was no relationship between the total amounts of NH_3-N evolved and total amounts of water evaporated from the soil. For instance, the total NH_3-N losses of 26.5, 23.2, and 16.9 percent of added N corresponded to water losses of 112, 107, and 236 ml, respectively.

Higher temperatures or higher air exchange rates may speed up NH_3-N losses during the time the soil is still moist. However, the total NH_3-N losses may be decreased because of the fewer days during which the soil is moist. This is evident in Table 9. It seems that adequate soil moisture is necessary for losses of NH_3-N to occur. The moisture maintains the NH_4^+ in solution and provides a medium to dissolve CO_2, carbonates, and calcium salts. Hydrolysis of urea also

Table 9. The NH_3-N losses (% of added N) at time intervals from Timpanogos soil as influenced by various temperatures created by a heat lamp and two rates of air flow over the soil surface.
N was applied to the soil surface at a rate of 100 kg N/ha with urea.

Time interval (day)	Exposed to the heat lamp		Shaded from the heat lamp			
	Low air rate† 31-38 C	High air rate† 30-41 C	Low air rate‡ 34-41 C	High air rate‡ 35-42 C	Low air rate† 22-24 C	High air rate† 22-24 C
1	0.67	1.72	1.28	1.45	0.26	0.46
2	2.20	3.66	3.50	2.81	0.85	1.05
3	5.99	4.61	7.04	0.93	1.95	2.93
4	3.91	0.65§	4.38	0.07§	2.03	2.08
5	4.15	2.61	3.79	2.19	2.01	2.65
6	1.80	0.91	2.36	1.08	2.33	1.69
8	1.76	0.37	1.77	0.29	1.27	1.10
10	1.50	0.19§	1.25	0.19§	0.51§	0.29§
15	1.20	2.20	1.08	2.69	0.46	2.37
Total NH_3-N losses, %#	23.18††c	16.92††b	26.45††c	11.70††a	11.67††a	14.62††ab
Total water losses, ml	107	236	112	229	62	177

†Averages of 2 observations

‡One observation

§On these dates 25 ml of distilled water was added to rewet the soil core to about 2.5 cm deep.

#Percentage of added NH_4-N

††Values with different letters are statistically different from each other.

takes place in water. Thus, adequate soil moisture provides for maximum opportunity for chemical reactions necessary to release NH_3-N. However, rewetting the soil will move some NH_4^+ and urea downward into the soil lowering the total NH_3-N eventually evolved.

Higher NH_3-N losses during the first days of drying occur in the rapid airflow rates compared to the slower flow rates. This is because the rate of NH_3-N loss is speeded by concentration of the solution during drying and by codistillation.

The NH_3-N volatilization has been found linearly related to the gas exchange rate in the soil up to 5 changes/hr (Overrein and Moe, 1967). But Bremner and Douglas (1971), and also Prasad (1976) agreed that the NH_3-N can be evolved from a constantly moist soil without subjecting the soil to moisture loss. The acid they used to trap the evolved NH_3-N reduced the NH_3 concentration in the air and thus in solution in proportion to NH_4^+, causing more NH_3-N to be formed and evolved from the soil solution. Therefore, any factor which changes the proportions of the NH_3-NH_4^+ concentrations in the soil solution will alter the amounts of NH_3-N lost.

The relation of conditions of N fertilizer application to calcareous soil on NH_3-N lost. Some conditions in which fertilizer may be added to soils in the field include: (1) incorporation into the soil by drilling, discing, or banding, (2) addition by broadcast to dry soil followed by moistening from dew or very light rainfall, and (3) broadcast on dry soil followed by rainfall or irrigation. Broadcast onto moist soil has already been discussed in the previous studies.

Incorporation of fertilizer into soil was done using the highly calcareous Millville silt loam soil. Ammonium sulfate at the rate of 200 kg N/ha was applied at 2.5, 5.0, and 7.5 cm depths to air-dry soil before the water equivalent to field capacity was added.

There was no NH_3-N lost during 14 days when the N fertilizers were placed at 2.5 cm or deeper. The lack of NH_3-N loss from even the shallowest depth (2.5 cm) is believed to be a result of the following reactions: (1) Part of the fertilizer dissolved and moved into deeper soil layers; and (2) the NH_4^+ and NH_3 formed were adsorbed to cation exchange sites and to particle surfaces as they moved upward toward the soil surface in water.

The second condition--adding N fertilizers to dry soil and having just light moisture such as dew or very light rainfall--was accomplished by passing air of high humidity across the soil surface. Ammonium sulfate, NH_4NO_3, or urea at the rate of 200 kg NH_4-N/ha was applied to the air-dry soil surface. The high-humidity air was obtained by bubbling the compressed air in distilled water before passing it across the soil surface.

The NH_3-N losses during 10 days from soil receiving $(NH_4)_2SO_4$, NH_4NO_3, and urea were 3.6, 34.2, and 2.4 percent of the added N, respectively. The relatively large NH_3-N loss from NH_4NO_3 was unexpected; the largest daily loss occurred in the first day (7.9 percent) and decreased with time (Table 10). Even by the tenth day the loss was still 1.3 percent. However, the daily rates of losses from $(NH_4)_2SO_4$ or urea were too small and not measured daily. The figures represent the total NH_3-N losses for 10 days.

Table 10. The NH_3-N losses at one-day intervals on highly calcareous Millville soil which received the equivalent of 200 kg NH_4-N/ha applied to the surface of air-dry soil before the air with a high humidity (compressed air bubbling in water) was passed over the soil surface.

Time (day)	NH_3-N loss, % of NH_4-N added†		
	$(NH_4)_2SO_4$	NH_4NO_3	Urea
1	-‡	7.9	-‡
2	-	4.7	-
3	-	4.0	-
4	-	3.2	-
5	1.4‡	3.4	0.9‡
6	-	3.6	-
7	-	2.3	-
8	1.4‡	2.0	0.9‡
9	-	1.8	-
10	0.8‡	1.3	0.6‡
Total	3.6	34.2	2.4

† Averages of 4 observations.

At the end of the experiment NH_4NO_3 and urea had completely dissolved and was not visible on the soil surface, but only parts of $(NH_4)_2SO_4$ applied dissolved.

‡ For samples with $(NH_4)_2SO_4$ or urea, measurements were not made daily but accumulated losses were measured at 5, 8 and 10 days.

The differences in NH_3-N losses among N sources were attributed to their solubilities. At the end of the experiment NH_4NO_3 and urea had completely dissolved and was not visible on the soil surface, but only parts of $(NH_4)_2SO_4$ applied had dissolved. Most of the NH_3-N formed from reactions of NH_4NO_3 and $CaCO_3$ on the soil surface was not retained in the soil because of their concentration in the limited moisture. Most of the NH_3-N should be readily volatilized. The small amounts of NH_3-N evolved from urea was the result of limited hydrolysis of urea caused by limited soil moisture.

The third condition--broadcast on air-dry soil surface followed by appreciable rainfall or irrigation--was simulated by adding the fertilizer to dry soil and wetting the soil. Each N fertilizer at the rate of 200 kg NH_4-N/ha was applied to the surface of the air-dry soil before the water equivalent to field capacity was added. The NH_3-N volatilized was trapped in 2 percent boric acid after the water on the soil surface had finished infiltration.

The amount of NH_3-N lost during 10 days from the soil receiving $(NH_4)_2SO_4$, NH_4NO_3, and urea were 15.0, 12.7, and 0.4 percent of the added N, respectively (Table 11). The NH_3-N losses from $(NH_4)_2SO_4$ and NH_4NO_3 were not different statistically.

The rates of NH_3-N losses from $(NH_4)_2SO_4$ and NH_4NO_3 were almost constant from day 1 to day 7. Urea is a very soluble fertilizer. Most of it might move downward with water and diffuse deeply enough for the soil to reatin any NH_3-N formed. Musa (1968) has reported that $(NH_4)_2SO_4$ and urea were found mostly in the top 5 cm and in the 18 to 23 cm, respectively, in the soil column

Table II. The NH_3-N losses in one-day intervals from highly calcareous Millville soil at room temperature.
The N fertilizers at a rate of 200 kg NH_4-N/ha were applied to the surface of air-dried soil before the amount of water to raise the soil moisture to field capacity was added.

Time (day)	NH_3-N loss, % of NH_4-N added†		
	$(NH_4)_2SO_4$	NH_4NO_3	Urea
1	1.6	1.6	-
2	1.9	1.8	-
3	1.7	1.5	-
4	1.8	1.4	-
5	1.8	1.4	0.3‡
6	1.7	1.4	-
7	1.6	1.2	-
8 §	1.2	0.9	-
9	1.0	0.9	-
10	0.7	0.6	0.1‡
Total	15.0	12.7	0.4

†Average of 4 observations.

§On this day 25 ml of distilled water was added to rewet the soil core to about 2.5 cm deep.

‡Measurements of NH_3-N from samples with urea were not measured daily, but, rather, were measured for the total accumulated loss at 5 and at 10 days.

after the 10 cm of water was added to a compact calcareous, clay soil column. Incomplete solubilization of NH_4NO_3 and $(NH_4)_2SO_4$ during wetting the soil and gradual movement back to the soil surface of dissolved portions may account for the continual low NH_3-N volatilization rates.

This study indicates that NH_3-N losses can be reduced by the application of N fertilizer to the air-dry soil surface just prior to a good rainfall or before the irrigation water is applied. The amount of reduction in NH_3-N losses from $(NH_4)_2SO_4$, NH_4NO_3, and urea are shown on Table 12.

Table 12. Reduction in the NH_3-N lost from calcareous Millville silt loam by the application of water after surface broadcasting of N fertilizer rather than wetting the soil prior to fertilization (or application on the wet soil surface).

Condition	NH_3-N loss, % of added N		
	$(NH_4)_2SO_4$	NH_4NO_3	Urea
Soil wetted before broadcast fertilization	43.0	22.1	18.2
Soil wetted after broadcast fertilization	15.0	12.7	0.4
Reduction, percent of added N	28.0	9.4	17.8
Percent decrease	(to one-third)	(to one-half)	(to no loss)

Field experiments

Environmental conditions, especially sunlight, temperature fluctuations, and drying of the soil surface, probably play important roles governing NH_3-N losses from the soil in the field. Therefore, some experiments were conducted to observe the effects of these factors as encountered in the field.

Effects of sunlight on NH_3-N losses from noncalcareous soil. The noncalcareous soil used was the Timpanogos soil. The condensation of water which would have occurred on the inside of the column was prevented by wrapping half of the column lengthwise and its top with the black polyethylene plastic sheets. Ammonium sulfate, NH_4NO_3, or urea at the rate recommended to growers (56 kg N/ha) was applied to the wet soil surface. The column was buried in the soil in such a way that the soil surface in the column and the field surface were level. The uncovered side of the column was exposed (faced) to the sun. This allowed the sunlight to strike the soil surface inside the column during the day time. The shaded columns were prepared similarly except that the covered plastic side was turned to the sunlight. Compressed air at a flow rate of 1500 cc/min was passed across the soil surface; the NH_3-N evolved from each cylinder was trapped in 80 ml of 2 percent boric acid in a 125 ml flask.

Preliminary tests indicated that the 2 cm soil temperatures inside the sunlight and shaded columns were nearly identical. The soil temperatures inside and outside the columns were recorded daily between 3 to 4 P.M. which was likely to be the period of the highest temperature on a clear day.

The sunlight did not alter the NH_3-N lost from the N fertilizers from Timpanogos soil. The average NH_3-N losses from the exposed and shaded soil during 8 days were 5.7 and 5.2 percent of the added N, respectively. Table 13 shows for one-day intervals the rates of NH_3-N loss from $(NH_4)_2SO_4$, NH_4NO_3, and urea. The total NH_3-N loss from $(NH_4)_2SO_4$ under both sunlight and shaded soils was the greatest. That lost from NH_4NO_3 was least.

The rate of NH_3-N loss was highest during the first day and decreased with time. This is different than was observed for urea in laboratory studies. In previous studies, urea had always had a lag time of about 3 days, presumably time for hydrolysis by the enzyme urease to occur. The reason for a lack of time lag here is unexplained.

Any differences in NH_3-N losses from samples exposed to sunlight and those exposed to shade was expected to be the results of small differences in the soil temperatures (Table 14). It is likely that the soil temperature inside and outside the columns were only slightly different on a clear day, but were the same on a cloudy day. Fenn and Kissel (1974) found that the temperatures (12 to 32 C) did not influence the NH_3-N loss at the lower rates of $(NH_4)_2SO_4$ they applied (33 and 66 kg NH_4-N/ha). Their results are in agreement with the results of this study.

The total NH_3-N loss from urea-treated soil exposed to sunlight was less than from soil in a shaded condition. This phenomenon is explained as follows: (1) The soil surface under sunlight dried rapidly, causing higher soil temperature; and (2) the rate of urea hydrolysis in the exposed column was lower due to

Table 13. Effects of sunlight on NH_3-N losses from untreated Timpanogos soil receiving 56 kg N/ha as different N sources applied on the wet soil surface.

Time (day)	NH_3-N loss, % of N added†					
	$(NH_4)_2SO_4$		NH_4NO_3		Urea	
	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade
1	3.6	2.5	1.4	1.1	1.8	1.5
2	1.4	1.4	0.5	0.7	0.9	1.4
3‡	0.8	0.9	0.2	0.3	0.2	0.9
4	1.0	0.9	0.5	0.5	0.8	1.3
5‡	0.4	0.3	-	-	-	-
6	0.7	0.6	0.6§	0.5§	0.9§	1.4§
7‡	-	-	-	-	-	-
8	0.6§	0.7§	0.3§	0.4§	0.8§	1.3§
Total	8.5 b	7.3 b	3.5 a	3.5 a	5.2 a	7.8 b

† Averages of 3 observations for $(NH_4)_2SO_4$ and NH_4NO_3, but only 2 observations for urea. Total NH_3-N loss values followed by the same letter are not significantly different at the 0.05 level.

‡ On these dates 30 ml of distilled water was added to rewet the soil surface.

§ The amounts of NH_3-N losses at day 6 for NH_4NO_3 and urea were the accumulated NH_3-N losses of day 5 and day 6. The amounts of NH_3-N losses at day 8 were the accumulated losses of day 7 and day 8.

insufficient moisture near or at the surface. The soil surface moisture is the major factor in controlling urea hydrolysis and the subsequent NH_3-N loss.

Table 14. Temperatures inside and outside soil columns used for determination of NH_3-N loss given in Table 13.

Time (day)	Temperatures (at 3 to 4 P.M.) C				Remarks
	Soil column at 2.0 cm soil depth		Outside column		
	Sunlight	Shade	2.0 cm Soil depth	Air	
0†	25	19	26	22	Clear
1	27	21	30	27	Clear
2	38	28	35	21	Clear
3ϕ	42	33	37	31	Clear
4	37	27	34	31	Clear
5ϕ	39	30	37	25	Mostly clear
6	24	23	25	21	Cloudy
7ϕ	19	18	20	15	Cloudy & showered
8	33	28	31	23	Clear

†About 2 hours after the soil surface was exposed to sunlight.
ϕSoil rewetted.

Effects of sunlight on NH_3-N losses from calcareous soil. The calcareous soil used was Millville silt loam. The methods used were similar to that used in the previous section of the field experiments. Table 15 lists NH_3-N losses from calcareous soil receiving N sources and exposed to sunlight or kept under shaded conditions. The soil temperatures are given in Table 16.

Table 15. Effects of sunlight on NH_3-N losses from highly calcareous Millville soil receiving 56 kg N/ha in different N sources applied to the wet soil surface.

Time (day)	NH_3-N loss, % of N added †					
	$(NH_4)_2SO_4$		NH_4NO_3		Urea	
	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade
1	37.4	27.0	11.2	7.5	3.5	1.9
2	10.6	9.9	4.8	3.5	3.2	2.2
3	4.6	8.4	2.1	3.3	0.8	2.4
4‡	1.5	4.0	0.9	2.1	0.3	0.9
5	3.3	3.8	1.7	2.0	0.9	1.1
6‡	1.3	2.9	0.6	1.6	0.3	0.9
7	2.7	2.8	1.4	1.5	1.3	1.4
Total	61.4 c§	58.8 c§	22.7 b§	21.5 b§	10.3 a§	10.8 a§

†Average of 3 observations for $(NH_4)_2SO_4$ and NH_4NO_3, but 2 observations for urea

‡On these dates 30 ml of distilled water was added to rewet the soil surface

§ Values with different letters are statistically different at the 95 percent confidence level

Table 16. Temperatures inside and outisde columns of Millville soil used for determinations of NH_3-N losses tabulated in Table 15.

Time (day)	Temperature (at 3 to 4 P.M.), C: Soil column at 2.0 cm depth, Sunlight	Soil column at 2.0 cm depth, Shade	Outside Column, 2.0 cm Soil Depth	Outside Column, Air	Remarks
0†	30	25	30	28	Clear
1	28	21	29	21	Clear
2	31	25	31	23	Clear
3	39	28	35	29	Clear
4ϕ	37	29	35	28	Partly cloudy
5	35	26	33	24	Partly cloudy
6ϕ	38	26	30	27	Partly cloudy
7	30	24	30	24	Partly cloudy

† About 3 hours after the soil surface was exposed to sunlight
ϕ Rewetting the soils

Sunlight did not affect NH_3-N loss. The averages of NH_3-N evolved was 31.4 and 30.5 percent of added N, when exposed to sunlight or kept in the shade, respectively. However, the NH_3-N losses from $(NH_4)_2SO_4$ the first day were exceptionally large; losses from all N sources decreased after the first day. Rewetting the air-dry soil surface increased the rates of NH_3-N losses. The order from greatest to least NH_3-N losses were $(NH_4)_2SO_4$ > NH_4NO_3 > urea.

Although soil temperatures at the 2 cm soil depth in sunshine or in shade were different, it had no significant effect on NH_3-N loss. Fenn and Kissel (1974) reported similar NH_3-N losses from calcareous soil within quite a temperature range of 12 to 32 C.

Perhaps there is an effect of temperature which simply alters the rate of loss by altering soil moisture. Samples exposed to sunlight had higher early losses of NH_3-N but as the soil dried, the NH_3-N loss decreased even below that from shaded columns. It is expected that if the samples exposed to sunlight, and thus having hotter temperatures, were kept moist, the total losses would exceed those from the shaded samples.

Effects of irrigation water applied after N fertilizer application. Ammonium sulfate, NH_4NO_3, or urea at a rate of 56 kg N/ha were applied to the calcareous Millville silt loam on the surface or at a 2.5 cm depth. The amount of water equivalent to field capacity was added to the soil surface in the column. All soil columns were exposed to sunlight. The NH_3-N evolved was trapped in 2 percent boric acid beginning immediately after the water on the soil surface had infiltrated.

No NH_3-N was volatilized from the highly calcareous soil receiving $(NH_4)_2SO_4$, NH_4NO_3, or urea applied at the 2.5 cm depth before the amount of field capacity water was added (Table 17), in spite of temperatures ranging from 30 to 42 C during the experimental period (Table 18). Even NH_3-N losses from soil with $(NH_4)_2SO_4$, NH_4NO_3, or urea applied to the soil surface followed by irrigation were reduced below losses when fertilizer was applied to wetted soil (compare Table 15 and 17). The losses under these conditions, reduced to less

Table 17. The NH_3-N losses at one-day intervals from highly calcareous Millville soil receiving 56 kg N/ha applied at the 2.5 cm depth or applied on air-dry soil before adding irrigation water to wet the soil to field capacity. The soil surface was exposed to sunlight.

	NH_3-N loss, % of N added†					
	$(NH_4)_2SO_4$		NH_4NO_3		Urea	
Time (day)	2.5 cm depth	Surface	2.5 cm depth	Surface	2.5 cm depth	Surface
1		8.5		4.0		0.6
2		2.8		1.0		-
3‡		3.3		1.4		0.3 §
4	None	1.8	None	0.6	None	-
5‡		0.9		0.3		-
6		3.3		1.5		1.0 #
7		0.5		0.2		0.3
Total losses	0.0	21.1 b††	0.0	9.0 a††	0.0	2.2 a††

† Averages of 2 observations

‡ On these dates 30 ml of distilled water was added to rewet the soil surface

§ Total NH_3-N loss of day 2 and 3

Total NH_3-N loss of day 4, 5, and 6

†† Values with different letters are statistically different at the 95 percent confidence level.

Table 18. Temperatures inside and outside Millville soil columns used for determination of NH_3-N losses given in Table 17.

Time (day)	Temperature (at 3 to 4 P.M.), C: Soil column 2.0 cm soil depth	Outside column 2.0 cm soil depth	Outside column Air	Remarks
0 †	35	33	31	Partly cloudy
1	33	31	31	Clear
2	40	38	31	Clear
3 ‡	37	33	31	Clear
4	42	41	33	Clear
5 ‡	32	30	30	Partly cloudy
6	30	30	28	Clear
7	42	41	31	Clear

†About 3 hours after the soil surface was exposed to sunlight
‡Rewetting the soil

than half of the loss when irrigation preceeded fertilizer additions, were still 21.1, 9.0, and 2.2 percent of added N, respectively. The highest losses from $(NH_4)_2SO_4$, NH_4NO_3 were again found in the first day.

The losses are explained just as was done for similar laboratory data. The very soluble urea moves into the soil with the water and is left deep in the soil, trapping any volatilized NH_3-N. The charged NH_4^+ and lower solubility of $(NH_4)_2SO_4$ leaves much of it at or near the soil surface, allowing appreciable

losses. Ammonium nitrate is somewhat intermediate between these two materials--very soluble but with a charged NH_4^+ ion.

It is evident that water application, rainfall or irrigation, after the N fertilizers were applied to the soil surface reduced the total NH_3-N losses to 34, 40 and 21 percent of the losses which occur from $(NH_4)_2SO_4$, NH_4NO_3, and urea, respectively, when these are added to wet soil.

SUMMARY AND CONCLUSIONS

This study compared the effects of nitrogen sources on the amount of mineral soil nitrogen; it included studies of nitrogen movement, and wheat yields when nitrogen fertilizers were applied to soil planted to dryland winter wheat at the Blue Creek Experimental Station in northern Utah. A laboratory study of ammonia-nitrogen loss from added fertilizer completed this study of nitrogen.

Nitrogen sources at the practical rate of 56 kg N/ha were broadcast before the winter wheat seed was drilled on September 17, 1973. The drill action covered most of the fertilizer to depths of 0-3 cm. Soil samples were taken on October 5, 1973, November 2, 1973, April 20, 1974, and May 18, 1974. The application of ammonium nitrate, ammonium sulfate, or S-coated urea increased the amounts of mineral nitrogen in the 0-30 cm layer during the fall samplings but not in the deeper soil. Samples from soil fertilized with ammonium nitrate had the largest amounts of mineral nitrogen. Decreasing amounts were obtained from soils fertilized with ammonium sulfate and S-coated urea. The soil sampling in spring the following year showed no difference in the amounts of mineral nitrogen found in the soil profiles fertilized with different nitrogen sources; the mineral nitrogen contained was similar in amounts to that in the unfertilized plot.

Soil treated by the different nitrogen sources produced grain yields similar to those from the unfertilized plots but produced significant increases in protein content and nitrogen content in the grain yield.

In studying the movement of nitrate-nitrogen in the soil profile, ammonium nitrate and potassium bromide at the rates of 400 kg N and 200 kg Br/ha, respectively, were broadcast (on October 10, 1974) after the wheat seed was drilled on October 5, 1974. The magnitudes of nitrate-nitrogen movement through the soil profile were estimated by the comparisons of the changes in the amounts of nitrogen and bromide in the soil profile at the beginning (November 5, 1974) and at the last soil samplings (May 28, 1975).

The patterns of the distributions of both nitrate-nitrogen and bromide contents in the soil profile on a given date were similar. On November 5, the highest amounts of nitrate-nitrogen and of bromide were found within the 15-30 cm depth. By May 28, after spring snow melted, the greatest amount of nitrate-nitrogen and bromide were within the 60-75 cm depth. Nitrate-nitrogen and bromide apparently moved down to the 150 cm depth, and probably deeper. At these maximum sampling depths, both nitrate and bromide concentrations were greater than those of the unfertilized plot. The nitrogen leaching below the 120 cm depth was estimated to be about 30 to 40 percent of the added nitrogen. This assumes little of the unaccounted-for nitrogen was volatilized as shown by ammonia loss studies. However, denitrification losses are unknown.

The heavy rate of nitrogen applied did not significantly increase grain yield, but did significantly increase straw yield, grain protein content, straw nitrogen content, and total nitrogen uptake in grain or in straw.

Different sizes of pelleted urea (from pulverized powder to 2.5 mm in diameter) did not affect the total amounts of ammonia-nitrogen losses from non-

calcareous Timpanogos soil after 14 days. From lower addition rates (50 and 100 kg N/ha), losses were similar (11.0 to 12.7 percent of added nitrogen), but from the higher rates (200 to 400 kg N/ha), the total ammonia-nitrogen lost increased (17.7 and 21.6 percent of added nitrogen, respectively).

From fertilized noncalcareous Timpanogos soil, the greatest loss of ammonia-nitrogen was from urea-treated soil (13.7 percent) followed by samples with ammonium sulfate (1.0 percent) and with ammonium nitrate (0.5 percent). But when calcareous Millville soil was used, the greatest loss in 14 days was from ammonium sulfate-treated soil (47.8 percent), followed by ammonium nitrate-treated soil (26.7 percent) and soil with urea (21.8 percent).

Increasing the soil pH or adding carbonates to the noncalcareous soil greatly increased the ammonia-nitrogen losses from soil receiving ammonium sulfate and ammonium nitrate, but had only a slight affect on losses from urea-treated soil. Carbonate in the soil (at pH 7.7) increased the ammonia-nitrogen loss compared to losses from soil having a similar pH created by sodium hydroxide solution addition when soils were fertilized with ammonium sulfate and ammonium nitrate. During 10 days losses from the samples receiving calcium carbonate or sodium hydroxide solution were 36.7 and 13.7 percent, respectively, of the added nitrogen added as ammonium sulfate. Corresponding figures for ammonium nitrate were 18.3 and 10.8 percent, respectively.

The higher rates of ammonia-nitrogen loss from the moist, fertilized soil occurred during the first 4 days from soil receiving ammonium sulfate and ammonium nitrate but during the period of day 3 to day 5 for urea. However, the

daily rate of water loss decreased only slightly until near the end of the experiment (10 days).

High temperature greatly increased the amounts of ammonia-nitrogen loss and water loss. But the highest ammonia-nitrogen loss required the persistence of both higher temperatures and a continual condition of moist soil.

Application of ammonium sulfate at a depth of 2.5 cm or deeper almost completely hindered ammonia-nitrogen loss from the calcareous soil. The reduced losses when ammonium sulfate and ammonium nitrate were applied to the soil surface before irrigation or a heavy rainfall moved the fertilizer into the soil were one-third or one-half, respectively, of the losses when the materials were added to wet soil surfaces. The loss from urea was also greatly reduced by this practice. Under the conditions of high humidity in the atmosphere but dry soil, ammonia-nitrogen was lost in greatest amount (34.2 percent) during 10 days from ammonium nitrate applied to the air-dry soil surface. The less soluble ammonium sulfate and uncharged soluble material (urea) had the least nitrogen loss.

Ammonia-nitrogen losses in the field were similar under either sunlight or shaded conditions when nitrogen fertilizers were applied to the wet soil surface at the practical rate of 56 kg N/ha. From noncalcareous soil, the amounts of ammonia-nitrogen lost in 7 days when exposed to sunlight were 8.5, 7.3, and 5.2 percent of the added nitrogen from soil supplied with ammonium sulfate, ammonium nitrate, and urea, respectively. Corresponding ammonia-nitrogen losses from calcareous soil were 61.4, 22.7, and 10.3 percent, respectively. The soil temperatures at the 2.0 cm depth were similar under sunshine or shaded

conditions. It is evident that soil receiving ammonium sulfate lost the greatest amount of ammonia-nitrogen, ammonium nitrate lost the next largest amount, and urea had the least loss.

Ammonia-nitrogen losses from calcareous Millville soil exposed to sunlight after materials were added to the wet soil surface were 61, 23, and 10 percent, respectively, for ammonium sulfate, ammonium nitrate, and urea. When irrigation (or heavy rainfall) followed the application of fertilizers to the air-dry soil surface, the respective losses of ammonia were reduced to 21, 9, and 2 percent. No ammonia-nitrogen loss was observed when ammonium sulfate was applied at a depth of 2.5 cm or deeper.

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APPENDIX

Table 19. Mineral N (kg/ha) in the 0-30 cm soil depth on October 5, November 2, 1973, April 20, and May 18, 1974. The soil received 56 kg N/ha with different N sources broadcast on the soil surface before winter wheat seed was drilled on September 17, 1973. Format: NH_4^+-N/NO_3^--N.

N source	Replicate 1	2	3	4	Average
		October 5, 1973			
Control	20/40	8/40	8/36	8/40	11/39
NH_4NO_3	91/143	63/119	12/63	67/131	58/114
$(NH_4)_2SO_4$	52/55	63/52	59/55	91/48	66/53
SCU	20/48	36/67	40/32	63/40	40/47
		November 2, 1973			
Control	8/40	8/16	4/36	4/16	6/27
NH_4NO_3	36/143	63/91	24/55	32/67	39/89
$(NH_4)_2SO_4$	71/83	103/55	87/55	71/48	83/60
SCU	87/115	32/32	16/52	40/32	44/58
		April 20, 1974			
Control	4/8	12/12	8/12	8/16	8/12
NH_4NO_3	8/12	12/4	4/16	8/20	8/13
$(NH_4)_2SO_4$	8/12	28/12	12/12	20/28	17/16
SCU	8/12	40/20	4/12	4/16	14/15
		May 18, 1974			
Control	4/8	12/8	12/8	8/4	9/7
NH_4NO_3	12/12	8/8	8/8	12/16	10/11
$(NH_4)_2SO_4$	8/4	4/4	8/8	8/4	7/5
SCU	20/12	8/4	12/12	48/12	22/10

Table 20. Mineral N (kg/ha) in the 30-75 cm soil depth on October 5, November 2, 1973, April 20, and May 18, 1974. Format: NH_4^+-N/NO_3^--N.

N source	Replicate 1	2	3	4	Average
		October 5, 1973			
Control	6/26	13/26	6/19	6/26	8/24
NH_4NO_3	26/45	38/38	35/26	6/19	27/32
$(NH_4)_2SO_4$	45/6	19/26	26/13	13/13	26/15
SCU	6/32	32/6	6/13	6/6	13/14
		November 2, 1973			
Control	6/19	6/26	6/26	6/13	6/21
NH_4NO_3	19/51	13/32	6/19	6/26	11/32
$(NH_4)_2SO_4$	26/38	19/26	6/26	6/19	14/27
SCU	13/38	6/13	6/26	13/19	10/24
		April 20, 1974			
Control	13/6	19/6	6/6	6/26	11/11
NH_4NO_3	13/45	13/6	6/13	6/38	10/26
$(NH_4)_2SO_4$	19/32	19/26	6/13	26/13	18/21
SCU	13/19	26/6	13/6	6/13	15/11
		May 18, 1974			
Control	19/6	19/6	13/6	13/6	16/6
NH_4NO_3	19/32	13/13	6/13	13/6	13/16
$(NH_4)_2SO_4$	13/38	19/13	19/16	19/13	18/18
SCU	13/26	13/13	13/6	13/6	13/13

Table 21. Mineral N (kg/ha) in the 75-120 cm soil depth on October 5, November 2, 1973, April 20, and May 18, 1974. Format: NH_4^+-N/NO_3^--N.

N source	Replicate 1	2	3	4	Average
			October 5, 1973		
Control	6/13	13/26	6/13	6/6	8/15
NH_4NO_3	26/70	6/13	13/6	13/26	15/29
$(NH_4)_2SO_4$	19/83	13/13	6/6	26/6	16/27
SCU	6/38	19/45	13/19	6/6	11/27
			November 2, 1973		
Control	13/51	6/26	6/6	13/26	10/27
NH_4NO_3	19/102	6/26	13/13	6/13	11/39
$(NH_4)_2SO_4$	6/38	13/26	6/19	13/6	10/22
SCU	13/38	6/13	6/26	13/19	10/24
			April 20, 1974		
Control	6/45	13/13	6/6	6/13	8/19
NH_4NO_3	6/90	6/19	6/6	6/38	6/38
$(NH_4)_2SO_4$	6/51	19/32	6/26	6/13	9/31
SCU	13/32	19/19	6/19	13/6	13/19
			May 18, 1974		
Control	13/26	13/13	13/13	6/13	11/16
NH_4NO_3	13/96	19/38	19/13	19/6	18/38
$(NH_4)_2SO_4$	19/83	19/32	13/19	13/6	16/35
SCU	19/45	19/19	13/6	13/13	16/21

Table 22. Sample analysis of variance for grain yield of dryland winter wheat grown in soil receiving 56 kg N/ha at the Blue Creek Experimental Station from September 1973 to July 1974.

Source	DF	SS	MS	F	$F_{.05}$
Total	15	3,412,229			
Replicate	3	2,664,833			
Treatment	3	294,030	98,010.2	1.95	3.86
Error	9	453,365	50,373.9		

	Treatment mean, kg/ha	LSD.05
Control	1,990	359
NH_4NO_3	2,292	
$(NH_4)_2SO_4$	2,290	
S-coated urea	2,322	

Table 23. Statistical summary of the results of the Experiment I.

Source	Treatment Mean				LSD .05
	Control	NH_4NO_3	$(NH_4)_2SO_4$	SCU	
Grain yield, kg/ha	1990	2292	2290	2322	359
Grain protein content, %	9.3	12.2	12.1	11.1	1.9
N content in grain, kg/ha	32.2	49.0	48.3	44.5	10.7
Mineral N in 0-30 cm depth:					
October 5, 1973	50	172	119	87	55.0
November 2, 1973	33	128	143	102	52.9
April 20, 1974	20	21	33	29	NS†
May 18, 1974	16	21	12	32	NS†

†The treatment means are not significantly different by the F-test, therefore LSD values were not calculated.

Table 24. NH_4-N content in the soil profile of unfertilized plots on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	NH_4-N, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	6	4	4	9	2	5	6	4	4	6
15-30	12	7	14	12	9	15	14	4	12	10
30-45	6	5	3	12	1	6	4	4	3	7
45-60	4	6	2	10	2	9	4	4	3	7
60-75		3	3	7	1	6		2	2	4
75-90		4	2	13	1	10		2	2	7
90-105		4	4	14	2	7		7	3	8
105-120		6	2	16	2	12		5	2	10
120-135		8		10		9		5		8
135-150		6		12		10		6		9
Total (0-120 cm)	-	39	34	67	20	70	-	32	31	59

Table 25. NO_3-N content in the soil profile of unfertilized plots on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	NO_3-N, kg/ha									
	Replicate I		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	13	6	10	4	10	5	10	5	11	5
15-30	37	1	37	5	28	11	23	4	31	5
30-45	13	3	10	6	11	7	7	4	10	5
45-60	10	6	9	5	6	5	5	6	7	6
60-75		10	6	7	2	6		10	4	8
74-90		15	5	2	3	5		8	4	8
90-105		19	6	11	4	9		3	5	10
105-120		19	13	8	3	5		5	8	9
120-135				7		11		6		10
135-150				6		9		6		10
Total (0-120 cm)	-	79	96	48	67	53	-	45	80	56

Table 26. NH_4-N content in the soil profile of fertilized plots on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	NH_4-N, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	223	26	372	48	258	55	324	62	294	48
15-30	15	7	13	10	17	8	6	8	13	8
30-45	17	8	23	9	10	5	20	8	18	8
45-60	5	8	5	10	5	11	6	6	5	9
60-75	5	11	4	12		6		11	5	10
75-90	4	16	5	8		10		2	4	9
90-105	3	12	5	29		8		3	4	13
105-120	6	15	3	9		7		5	5	9
120-135		9		10		7		12		10
135-150		13		12		6		4		9
Total (0-120 cm)	278	103	430	135	-	110	-	105	348	114

Table 27. NO_3-N content in the soil profile of fertilized plots on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	NO_3-N, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	113	28	119	45	95	38	72	27	100	35
15-30	131	18	186	21	124	14	225	15	167	17
30-45	17	21	19	27	10	35	23	21	17	26
45-60	8	25	11	91	3	52	10	61	8	57
60-75	3	46	9	91		55		61	6	63
75-90	4	36	11	49		36		63	8	46
90-105	4	36	13	26		30		41	9	33
105-120	9	27	21	22		24		28	15	25
120-135		30		35		20		27		28
135-150		16		51		14		22		26
Total (0-120 cm)	289	237	389	372	-	257	-	317	330	302

Table 28. Bromide content of the control plots on November 5, 1974 and May 28, 1975 of the Experiment II.

Depth (cm)	Br^- kg/ha Replicate 1		2		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	2	0	2	2	2	1
15-30	2	2	3	2	3	2
30-45	2	2	2	2	2	2
45-60	1	1	4	1	3	1
60-75	2	2	4	4	3	3
75-90	2	3	5	2	4	3
90-105	4	2	7	3	6	3
105-120	1	6	8	8	5	7
120-135		7		8		8
135-150		11		5		8
Total (0-120 cm	16	18	35	24	28	22

Table 29. Bromide content of the KBr-added plots in the soil profile on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	Br^-, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	28	0	105	4	66	2	59	1	65	2
15-30	78	1	165	3	97	4	148	2	122	3
30-45	19	2	32	3	21	14	13	7	21	6
45-60	4	2	8	5	11	53	4	15	7	19
60-75		21	6	14	5	70		44	6	37
75-90		34	4	17	5	43		49	4	36
90-105		40	2	6	5	15		52	3	28
105-120		51	2	9	8	16		47	5	31
120-135		45		6		12		21		21
135-150		40		5		13		23		21
Total (0-120 cm)	-	115	324	61	209	217	-	217	233	162

Table 30. Total N content (kg/ha) in the soil profile of the unfertilized plots on November 5, 1974 and May 28, 1975.

Depth (cm)	Total N, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	1988	2116	1919	1946	1851	1640	1753	1804	1878	1876
15-30	2126	2216	2341	2293	2132	2032	1876	1990	2119	2134
30-45	2030	2102	2162	2241	1983	1808	1615	1834	1947	2000
45-60	1708	1736	1966	1979	1610	1646	1463	1536	1687	1725
60-75		1408	1580	1508	1523	1472		1429	1553	1455
75-90		1357	1401	1344	1314	1267		1401	1359	1342
90-105		1148	1255	1282	1161	1199		1312	1208	1235
105-120		1286	1235	1144	1233	1184		1327	1235	1235
120-135		1401		1250		1235		1188		1270
135-150		1195		1327		1208		1135		1216
Total (0-120 cm)		13,371	13,861	13,751	12,807	12,250		12,634	12,986	13,002

Table 31. Total N in the soil profile of the fertilized plots on November 5, 1974 and May 28, 1975 (Experiment II).

Depth (cm)	Total N, kg/ha									
	Replicate 1		2		3		4		Average	
	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28	Nov. 5	May 28
0-15	2336	2048	2635	2164	1947	1749	2387	2085	2327	2011
15-30	2263	2117	2371	2443	1971	1834	2314	2138	2229	2134
30-45	2072	2021	2315	2294	1495	1595	2087	2006	1994	1979
45-60	1734	1655	2002	1987	1384	1384	1725	1917	1713	1736
60-75	1472	1419	1593	1751		1233		1623	1534	1506
75-90	1312	1297	1348	1493		1399		1693	1331	1472
90-105	1263	1220	1387	1325		1353		1436	1325	1333
105-120	1108	1233	1374	1284		1116		1318	1242	1238
120-135		1312		1380		1159		1161		1252
135-150		1227		1163		1304		997		1174
Total (0-120 cm)	13,561	13,011	15,025	14,741	-	11,664	-	14,218	13,695	13,409

Table 32. Individual replicate data of winter wheat yields of the Experiment II.

Yield component	Replicate 1	2	3	4	Average
Control plots:					
Grain yield, kg/ha	1595	2573	1658	1411	1809
Grain protein content, %	15.1	12.1	12.8	12.9	13.2
Straw yield, kg/ha	2178	4598	2649	2188	2903
Straw N content, %	0.42	0.26	0.28	0.28	0.31
N uptake in grain, kg/ha	42	56	37	32	42
N uptake in straw, kg/ha	10	13	8	6	9
Fertilized plots:					
Grain yield, kg/ha	1916	2296	2643	2542	2349
Grain protein content, %	20.4	20.2	18.6	19.3	19.6
Straw yield, kg/ha	6286	8255	6885	6056	6871
Straw N content, %	0.70	0.70	0.55	0.45	0.60
N uptake in grain, kg/ha	69	82	86	85	81
N uptake in straw, kg/ha	44	58	38	28	42

Table 33. Accumulative NH_3-N losses (percent of added N) from the soils under different conditions at room temperature in the Experiment III.

Condition	Replicate 1	2	3	4	5	Average
Different sizes of urea pellets from Timpanogos soil (14 days)						
2.00-2.50 mm diameter	6.2	7.0	7.4			6.8
1.34-2.00 mm	10.7	10.1	7.2			9.3
0.59-1.34 mm	8.6	11.2	11.2			10.3
Pulverized urea	11.1	9.2	11.6			10.7
Different N sources from Timpanogos soil (13 days)						
$(NH_4)_2SO_4$	1.0	1.0	0.9	1.0	0.8	0.9
NH_4NO_3	0.5	0.5	0.5	0.5	0.6	0.5
Urea	16.3	14.4	14.3	11.6	14.1	14.1
Different rates of urea from Timpanogos soil (14 days)						
50 kg N/ha	11.3	10.9	12.4	9.3		11.0
100	15.2	12.7	12.2	10.5		12.7
200	20.3	16.7	17.3	16.5		17.7
400	20.5	24.1	20.9	21.1		21.6
Timpanogos soil + 5% by weight $CaCO_3$ (14 days)						
$(NH_4)_2SO_4$	36.8	39.6	39.4	38.0	34.5	37.6
NH_4NO_3	18.8	16.8	18.1	17.5	20.2	18.3
Urea	16.8	15.4	17.6	14.5	13.0	15.5
Timpanogos soil + 5% by weight $BaCO_3$ (14 days)						
$(NH_4)_2SO_4$	60.2	61.9	53.4	58.1	63.9	59.5
NH_4NO_3	45.4	46.8	44.9	42.8	46.2	45.2
Urea	19.1	20.5	23.3	20.9	16.8	20.1
Millville soil (18 days)						
$(NH_4)_2SO_4$	51.1	47.6	46.2	53.0	51.1	49.8
NH_4NO_3	28.7	32.2	31.2	26.5	29.5	29.6
Urea	24.8	26.8	17.6	29.5	22.2	24.2

Table 33. Continued

Condition	Replicate 1	2	3	4	5	Average
Timpanogos soil at different pH values (14 days)						
pH 7.4:						
$(NH_4)_2SO_4$	4.6	4.6	5.3			4.9
NH_4NO_3	4.4	4.4	4.0			4.2
Urea	20.0	16.6	19.1			18.6
pH 8.4:						
$(NH_4)_2SO_4$	28.0	29.0	30.0			29.3
NH_4NO_3	19.6	21.8	21.1			20.8
Urea	22.6	25.2	20.4			22.7
Timpanogos soil (10 days)						
Addition of 10% $CaCO_3$:						
$(NH_4)_2SO_4$	35.9	29.3	42.1	39.3		36.6
NH_4NO_3	20.1	18.1	17.6	17.3		18.3
Addition of NaOH solution:						
$(NH_4)_2SO_4$	12.1	13.8	14.2	14.5		13.7
NH_4NO_3	11.5	11.6	10.4	9.5		10.8
N application to Millville soil before irrigation (10 days)						
$(NH_4)_2SO_4$	12.0	15.8	14.6	18.1		15.1
NH_4NO_3	11.5	11.4	13.1	14.5		12.6

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